Indo American Journal of Multidisciplinary Research and Review (IAJMRR)
International Peer Reviewed - Refereed Research Journal
ISSN: 2581 - 6292, Impact Factor: 6.885, Website: www.iajmrr.com

INTELLIGENT ADAPTIVE ENERGY MANAGEMENT SYSTEM FOR STANDALONE EV WITH DYNAMIC POWER FLOW OPTIMIZATION AND BATTERY PROTECTION

M. Asaithambi*, R. Thillainayaki, V. Sneha** & A. Suma****
* Assistant Professor, Department of Electrical and Electronics Engineering, Dhanalakshmi Srinivasan Engineering College (Autonomous), Perambalur, Tamil Nadu, India
** UG Student, Department of Electrical and Electronics Engineering, Dhanalakshmi Srinivasan Engineering College (Autonomous), Perambalur, Tamil Nadu, India

---

Cite This Article: M. Asaithambi, R. Thillainayaki, V. Sneha & A. Suma, "Intelligent Adaptive Energy Management System for Standalone EV with Dynamic Power Flow Optimization and Battery Protection", Indo American Journal of Multidisciplinary Research and Review, Volume 10, Issue 1, January - June, Page Number 94-102, 2026.

Type of Review: Peer Reviewed as per |C|O|P|E| Guidance.

DOI: https://doi.org/10.5281/zenodo.19782961

Abstract:

This system presents an advanced Energy Management System (EMS) for a standalone Electric Vehicle (EV), incorporating photovoltaic panels and batteries as primary power sources, with Peltier modules serving as secondary sources. An intelligent adaptive PID controller is employed to optimize power flow and manage residual energy, directing it towards a dump load when necessary. The system is designed to enhance efficiency and reliability under variable renewable energy conditions and load fluctuations. A nonlinear PID controller ensures effective voltage regulation, maintaining the output voltage within desired limits. Comparative analysis with PID and sliding mode controllers—recognized benchmark techniques for EVs demonstrates the proposed system's superior performance. The proposed EMS achieves global asymptotic stability under dynamic load conditions and effectively manages battery output to prevent damage during sudden increases in EV speed via throttle adjustments. Simulation and hardware results validate the effectiveness of the proposed control system, showcasing its ability to maintain optimal performance and stability in real-world scenarios.

1. Introduction:

1.1 Background of the Study:

The rapid evolution of Electric Vehicles (EVs) has intensified the global demand for highly efficient, stable, and intelligent Energy Management Systems (EMS). EVs operating in standalone or off-grid environments face unique challenges due to their dependency on renewable energy sources, battery capacity, and dynamic load variations. As renewable energy technologies such as photovoltaic (PV) panels become widely integrated into EV architectures, the need for advanced power optimization mechanisms has become increasingly significant.

Traditional EMS frameworks typically rely on fixed control strategies that struggle to maintain system stability during fluctuating environmental conditions, sudden acceleration, or variable load requirements. To address these limitations, modern systems incorporate adaptive and nonlinear controllers capable of managing energy flow intelligently, ensuring prolonged battery life, enhanced efficiency, and stable power delivery.

This project focuses on the development of an advanced EMS incorporating PV panels, batteries, and Peltier modules, supported by an adaptive nonlinear PID controller for improved operational performance under real-world disturbances.

2. Problem Statement:

Standalone EVs experience significant difficulties in maintaining stable power output due to their dependence on fluctuating renewable sources and unpredictable load conditions. Conventional PID controllers fail to provide consistent performance under nonlinear dynamics, leading to voltage instability, battery stress, and inefficient power distribution.

Additionally, residual or excess energy generated during optimal conditions is frequently wasted due to the absence of an intelligent dump load management system. Sudden load variations, especially during throttle-based acceleration, may also cause voltage drops and battery degradation. Therefore, there is a critical need for a smart energy management solution capable of stabilizing voltage, optimizing power flow, and improving vehicle reliability under diverse operating scenarios.

3. Objectives of the Study:

The primary objectives of the proposed system are as follows:

- To design and develop an advanced standalone Energy Management System (EMS) for EVs, integrating PV panels, batteries, and Peltier modules as energy sources.
- To implement an adaptive nonlinear PID controller for optimal voltage regulation and power flow management under dynamic load conditions.
- To incorporate an intelligent dump load mechanism for efficient utilization of excess or residual energy.
- To compare the performance of the proposed controller with traditional PID and sliding mode controllers.
- To validate system performance through simulation and hardware experiments, ensuring stability, reliability, and real-time applicability.

1.4 Scope of the Project:

This project primarily focuses on the development of a reliable Energy Management System (EMS) for standalone EV applications, emphasizing advanced control techniques and renewable energy integration. The work includes modeling energy sources, implementing nonlinear PID control, performing comparative analysis with benchmark techniques, and validating results through simulations and hardware setups.

The scope encompasses power optimization, voltage regulation, stability analysis, and energy distribution, but excludes vehicle body design, mechanical components, and communication-based smart grid integration.

1.5 Significance of the Study:

This project contributes to the field in multiple ways:

- It introduces an intelligent EMS capable of handling nonlinearities inherent in EV power systems.
- It enhances the longevity and safety of EV batteries by preventing overloading and sudden voltage drops.
- It ensures efficient energy utilization by redirecting excess energy to a dump load.
- It provides an in-depth comparison of modern control strategies, demonstrating the superiority of adaptive nonlinear PID control.
- It supports the growing need for renewable energy-driven transportation systems.

1.6 System Overview:

The proposed EMS integrates three primary energy components PV panels, batteries, and Peltier modules. PV panels act as the dominant renewable power source, capturing solar energy, while batteries serve as the primary storage component, ensuring continuous power delivery.

Peltier modules operate as auxiliary power sources, supplying additional energy during high demand. A nonlinear adaptive PID controller monitors voltage and load variations, adjusting power distribution dynamically. During periods of excess energy generation, the controller diverts surplus energy to a dump load, thereby preventing system instability.

The integration of renewable generation, storage, and intelligent control results in a more resilient and reliable EV energy system.

1.7 Challenges in Existing Systems:

Existing EV energy management systems suffer from:

- Inability to regulate voltage effectively under nonlinear and dynamic conditions.
- Inadequate utilization of residual energy from renewable sources.
- Lack of robust controllers capable of maintaining global stability during sudden load changes.
- Poor battery protection under rapid acceleration or variable driving conditions.
- Insufficient integration of secondary sources such as Peltier modules.

These challenges highlight the need for a next-generation EMS with intelligent, dynamic control capabilities.

1.8 Need for Adaptive Nonlinear PID Control in EV Energy Systems:

Conventional PID controllers operate effectively under linear, static conditions but perform poorly in the presence of nonlinear behaviors typical of EV power systems. Load variations, renewable fluctuations, and sudden surges in demand require a control strategy capable of real-time adaptation. The nonlinear PID controller in this system ensures:

- Accurate voltage regulation
- Smooth power distribution
- Reduced control errors during dynamic conditions
- Global asymptotic stability
- Minimum overshoot and optimal settling time

This makes nonlinear PID an ideal solution for EV EMS applications.

1.9 Comparative Importance of Benchmark Controllers:

To establish the superiority of the proposed system, it is compared with two widely used benchmark controllers:

- Traditional PID Controller - Simple but ineffective in nonlinear environments.
- Sliding Mode Controller (SMC) - Robust but suffers from chattering, leading to power losses and hardware stress.

Results from the comparative analysis reveal that the adaptive nonlinear PID controller delivers better stability, energy efficiency, and reliability across all tested conditions.

2. Literature Survey:

2.1 N. Yang, Y. Wang, Y. Zhang, and D. Yuan (2025) - Non-Intrusive Load Monitoring for Energy Management in Smart Grids Incorporating EVs:

Yang et al. (2025) present an innovative approach to enhancing smart grid energy management by integrating Non-Intrusive Load Monitoring (NILM) for effective load disaggregation, especially in environments with high electric vehicle (EV) penetration. Their work highlights the increasing complexity of managing flexible residential loads driven by EV charging demands and variability in household appliance usage. The authors propose the Serial Multi-task Transformer with Attention (SMTA), an advanced NILM algorithm capable of analyzing long-term aggregated smart meter data. The model incorporates serial correlation mechanisms, cyclical time-series analysis, and task-specific attention to accurately identify appliance-level power usage. This approach addresses limitations in traditional NILM methods, such as inaccurate disaggregation, privacy concerns, and difficulty in handling overlapping load signatures. The integration of NILM outputs into an energy management model reduces net operational costs. Using the IEEE 57-bus system and real-world datasets, the framework improves disaggregation accuracy and reduces operational costs by up to 26.9%.

2.2 O. A. Talaband and I. Avci (2025) - Energy Management in Microgrids Using Model-Free Deep Reinforcement Learning Approach:

Talaband and Avci (2025) address challenges in microgrid energy management caused by renewable variability and EV charging demand. Traditional approaches relying on uncertainty modeling become inefficient under dynamic conditions. They propose a model-free Deep Reinforcement Learning (DRL) framework using the Deep Deterministic Policy Gradient (DDPG) algorithm, formulating the problem as a Markov Decision Process (MDP). This enables real-time adaptation without requiring probabilistic forecasting models. Simulation results show reduced power losses and operational costs, achieving a 3.19% cost reduction compared to Dueling DQN and 4% compared to conventional DQN methods. The model demonstrates scalability and robustness in uncertain environments.

2.3 M. Arsalan Jalees Abro et al. (2025) - A Black-Box Approach to EV Energy Consumption: Integrating Key Parameters for Drive Range Optimization:

Abro et al. (2025) propose a black-box modeling framework to improve EV drive range estimation by integrating 23 parameters, including environmental conditions, vehicle dynamics, battery characteristics, and driver behavior. Using AVL eSuite simulations and real-world data from the Nissan Leaf SV Plus, the model significantly improves prediction accuracy. It identifies key overlooked factors such as regenerative braking efficiency, HVAC usage, and auxiliary loads. The study contributes to reducing range anxiety and improving EV efficiency, while also supporting future AI-based energy optimization systems.

2.4 Y. Farajpour, A. Lotfy, H. Chaoui, and S. Kelouwani (2025) - Cutting-Edge EMS Technologies for EVs and HEVs: Recent Developments and Future Directions:

Farajpour et al. (2025) provide a comprehensive review of Energy Management Strategies (EMS) for EVs and Hybrid EVs (HEVs). They classify EMS techniques into rule-based, optimization-based, and intelligent transportation system (ITS)-based approaches. The study highlights advancements such as machine learning integration, predictive control, wireless charging, and V2X communication. Challenges identified include computational complexity, real-time implementation issues, and grid-vehicle coordination. The authors emphasize the need for adaptive and intelligent EMS solutions for future EV systems.

2.5 R. Çakmak, G. Bayrak, and M. Koç (2025) - A Fuzzy Logic-Based Energy Management Approach for Fuel Cell and Photovoltaic-Powered EV Charging Station in DC Microgrid Operations:

Çakmak et al. (2025) propose a fuzzy logic-based EMS for DC microgrids integrating fuel cells and photovoltaic systems for EV charging stations. The controller efficiently manages nonlinear renewable behavior without requiring complex mathematical models. Simulation results show improved stability, reduced power losses, and enhanced renewable energy utilization. The system ensures uninterrupted EV charging while protecting storage components and fuel cells.

2.6 M. Tanjil Sarker et al. (2025) - Performance Evaluation of Second-Life EV Batteries for Off-Grid Solar Energy Storage System:

Sarker et al. (2025) investigate the use of second-life EV batteries for off-grid solar energy storage. Batteries from different chemistries are tested through extensive charge discharge cycles. Results indicate that LFP batteries provide superior thermal stability and lifecycle performance. The study highlights the importance of intelligent Battery Management Systems (BMS) to handle degradation and irregular load patterns.

2.7 V. Srimathi and D. Vijayakumar (2025) - Design and Implementation of Power Management System in Multi-String Solar-Interfaced DC Microgrid with Energy Storage System:

The authors propose a condition-based Power Management Algorithm (PMA) for DC microgrids with solar and EV battery integration. The system maintains stable DC bus voltage under varying conditions. Implemented on an FPGA controller, the system demonstrates improved voltage regulation, power quality, and battery protection. It supports seamless mode transitions and efficient energy distribution.

2.8 D. Tavangar Rizi et al. (2025) - Sustainable Smart Energy Hub Design with V2H Interfaces Using Deep Q-Learning:

Rizi et al. (2025) address cyber security challenges in smart energy hubs integrating EVs and thermal systems. They propose a Deep Q-Learning (DQN)-based approach to detect and correct manipulated data. The method significantly reduces system errors and improves stability, ensuring reliable operation under cyber threats.

2.9 T. H. M. Sumon Rashid et al. (2025) - Strategic Integration of Battery Energy Storage Systems for EV Charging Demand Management:

Rashid et al. (2025) propose a multi-criteria decision-making (MCDM) approach combined with differential evolution for optimizing BESS in EV charging systems. The strategy improves voltage stability, reduces costs, and enhances grid flexibility, making it suitable for transactive energy markets.

2.10 A. Singh and B. K. Panigrahi (2025) - Prosumer Cost Efficiency and Grid Stability Using Hierarchical PPO Framework:

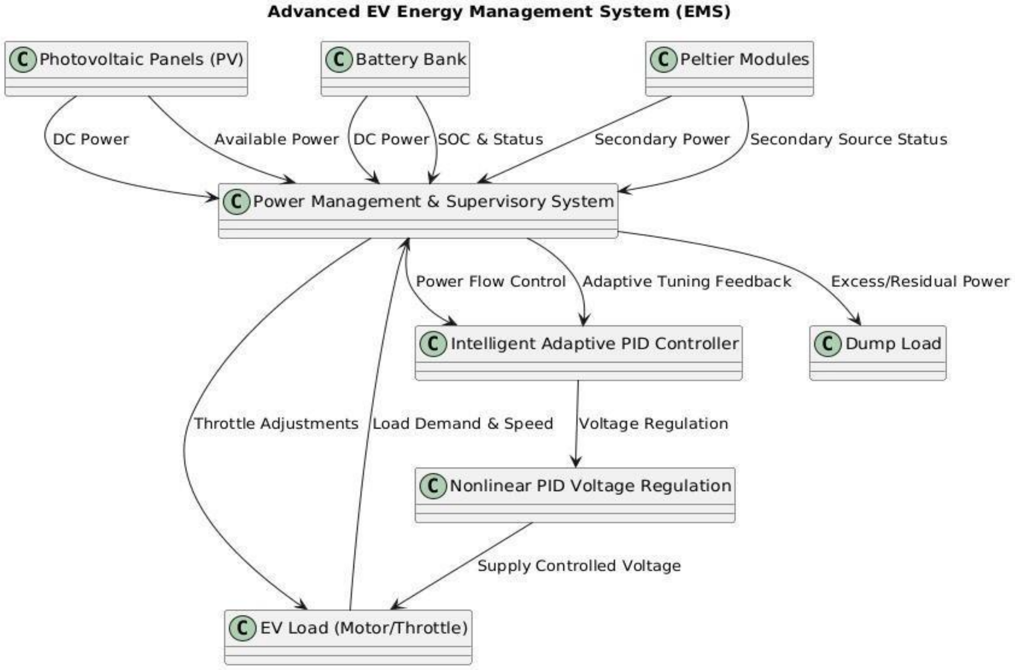
Singh and Panigrahi (2025) introduce a hierarchical reinforcement learning framework (H2EN-PPO) for decentralized energy management. The system optimizes pricing, scheduling, and EV charging. Simulation results show reduced energy costs and improved grid stability, highlighting the importance of AI-driven EMS in future smart communities.

3. Methodology:

3.1 Existing System:

Existing energy management methodologies for standalone electric vehicles primarily rely on conventional renewable integration techniques and basic PID-based voltage regulation. These systems generally incorporate photovoltaic (PV) panels and batteries as the main energy sources, with power converters employed to maintain stable operation. The control strategies used in most existing systems are static and linear, designed to operate only under steady-state conditions. As a result, they exhibit limited adaptability to sudden changes in load, fluctuating solar irradiance, battery state-of-charge (SOC) variations, and rapid acceleration caused by throttle adjustments.

In traditional EV architectures, excess energy produced by PV modules during peak sunlight hours is often left unutilized or insufficiently controlled due to the absence of intelligent dump load mechanisms. Similarly, voltage drops occurring during sudden increases in motor demand can push the battery into stress conditions, accelerating degradation. Sliding Mode Controllers (SMC) and classical PID controllers are occasionally used, but these too face performance issues under nonlinear dynamic conditions, especially when the EV undergoes unpredictable load variations. Thus, existing systems lack robustness, real-time adaptability, and efficient residual energy management, making them unsuitable for next-generation standalone EV applications where stability, reliability, and energy optimization are crucial.



3.2 Disadvantages of Existing System:

- Poor Performance under Nonlinear Dynamics: Traditional PID controllers fail to maintain stability during sudden load changes, voltage disturbances, and irregular renewable generation.
- Absence of Adaptive Control: Existing controllers do not self-adjust to environmental variations, leading to overshoot, longer settling time, and voltage instability.
- Inefficient Energy Utilization: Residual or excess solar energy is not efficiently managed due to the lack of dump load mechanisms.
- Battery Stress and Faster Degradation: Rapid throttle changes cause sudden current surges that damage battery cells due to poor load distribution.
- Limited Integration of Secondary Sources: Peltier modules or other thermoelectric sources are rarely integrated, reducing total available power during demand spikes.
- Inability to Achieve Global Asymptotic Stability: Benchmark controllers like Sliding Mode Controller (SMC) suffer from chattering, while classical PID is ineffective under dynamic conditions, reducing long-term stability.

3.3 Proposed System:

The proposed system introduces a smart standalone Energy Management System (EMS) for an electric vehicle integrating:

- Primary Sources: Photovoltaic (PV) panel and battery
- Secondary Auxiliary Source: Peltier modules
- Intelligent Controller: Adaptive Nonlinear PID Controller
- Energy Dissipation Mechanism: Dump Load System
- Benchmark Comparison: Classical PID and Sliding Mode Controller (SMC)
- Development and Validation Platform: MATLAB/Simulink simulations and hardware prototype

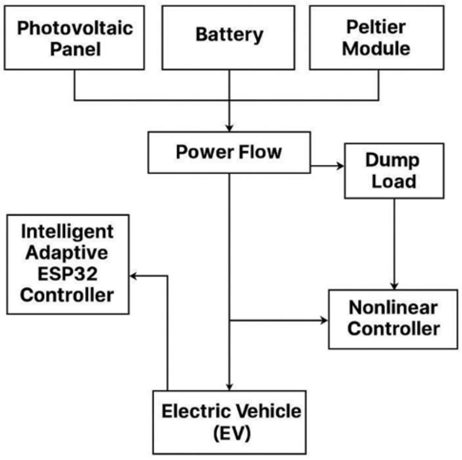
The EMS is designed to intelligently regulate voltage and manage power flow among different energy sources based on real-time load conditions and renewable energy availability. The nonlinear PID controller adapts to disturbances, ensuring stable voltage output, reduced transient errors, and global asymptotic stability.

Excess energy is automatically directed to a dump load, preventing voltage spikes and inefficient energy wastage. A dynamic throttle-based load model simulates EV acceleration and deceleration, allowing the controller to optimize battery discharge rates and prevent sudden stress on the battery. The entire system is validated using MATLAB simulations, followed by real-world hardware implementation for performance verification.

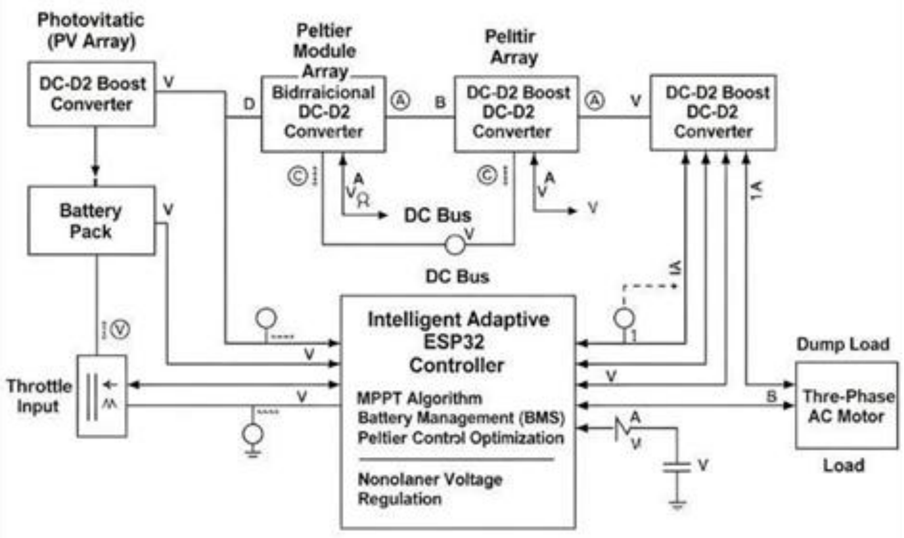
3.4 Advantages of Proposed System:

- Improved Voltage Stability: The nonlinear PID controller ensures accurate and stable voltage regulation under fluctuating environmental conditions.
- Adaptive Power Flow Optimization: Automatically adjusts control parameters to maintain optimal energy distribution among PV panels, batteries, and Peltier modules.
- Enhanced Energy Utilization: Efficiently manages excess energy using a dump load mechanism, minimizing wastage.
- Battery Protection: Reduces stress on batteries by controlling sudden current surges during rapid load variations.
- Global Asymptotic Stability: Achieves superior performance compared to traditional PID and SMC controllers under dynamic conditions.
- Real-World Feasibility: MATLAB simulations combined with hardware results confirm real-time applicability and robust performance.

BLOCK DIAGRAM OF PROPOSED EMS



Architecture Diagram:



Advanced EV Energy Management System Circuit Diagram

3.5 Module Description:

3.5.1 Photovoltaic (PV) Module:

- Functions as the primary renewable energy source.
- Converts solar irradiance into electrical energy.
- Output voltage is fed into a DC-DC converter for regulation.

3.5.2 Battery Storage System:

- Stores energy for use during low sunlight conditions.
- Supplies power during sudden load increases or throttle boosts.
- Continuously monitored to prevent over-discharge and over current.

3.5.3 Peltier Module (Secondary Source):

- Serves as an auxiliary power source.
- Supports the system during fluctuations or high-demand events.
- Enhances system reliability during cloudy or low-energy periods.
- **3.5.4 DC-DC Converters:**
- Stabilize voltage from PV and Peltier modules.
- Interface energy sources with the load and controller.

3.5.5 Adaptive Nonlinear PID Controller:

- Main controller responsible for voltage regulation.
- Dynamically adjusts control gains based on real-time error and system conditions.
- Ensures global stability with minimized overshoot.

3.5.6 Dump Load:

- Absorbs excess energy generated by PV panels.
- Prevents overvoltage and improves energy utilization.

3.5.7 EV Load Model:

- Represents the EV motor and throttle-driven load variations.
- Simulates sudden acceleration and deceleration.

3.5.8 MATLAB/Simulink Simulation Module:

- Used for system modeling, controller tuning, performance analysis, and validation.
- Provides insights into transient and steady-state behavior.

3.6 MATLAB Simulation Process:

3.6.1 System Modeling in Simulink:

- PV and battery modeled using standard Simscape libraries.
- Converters designed using PWM control blocks.
- Load variations implemented using time-dependent functions.

- Controller modeled using custom subsystem blocks.

3.6.2 Simulation Test Cases:

- Sudden throttle increase
- Low irradiance condition
- High irradiance with dump load activation
- Battery low state-of-charge (SOC) condition
- Comparative study with PID and SMC

3.6.3 Output Analysis:

Simulation outputs include:

- Voltage stability curves
- Transient response graphs
- Power distribution patterns
- Battery discharge profiles
- Comparative controller performance plots

4. Software Implementation:

4.1 Software Description:

MATLAB is a powerful and flexible tool widely used for data analysis, modeling, and simulation. Although not primarily a data mining tool like Weka or Clementine, MATLAB is frequently used in combination with other platforms due to its strong computational capabilities. It provides an interactive environment for numerical computation, visualization, and programming, making it highly suitable for engineering applications.

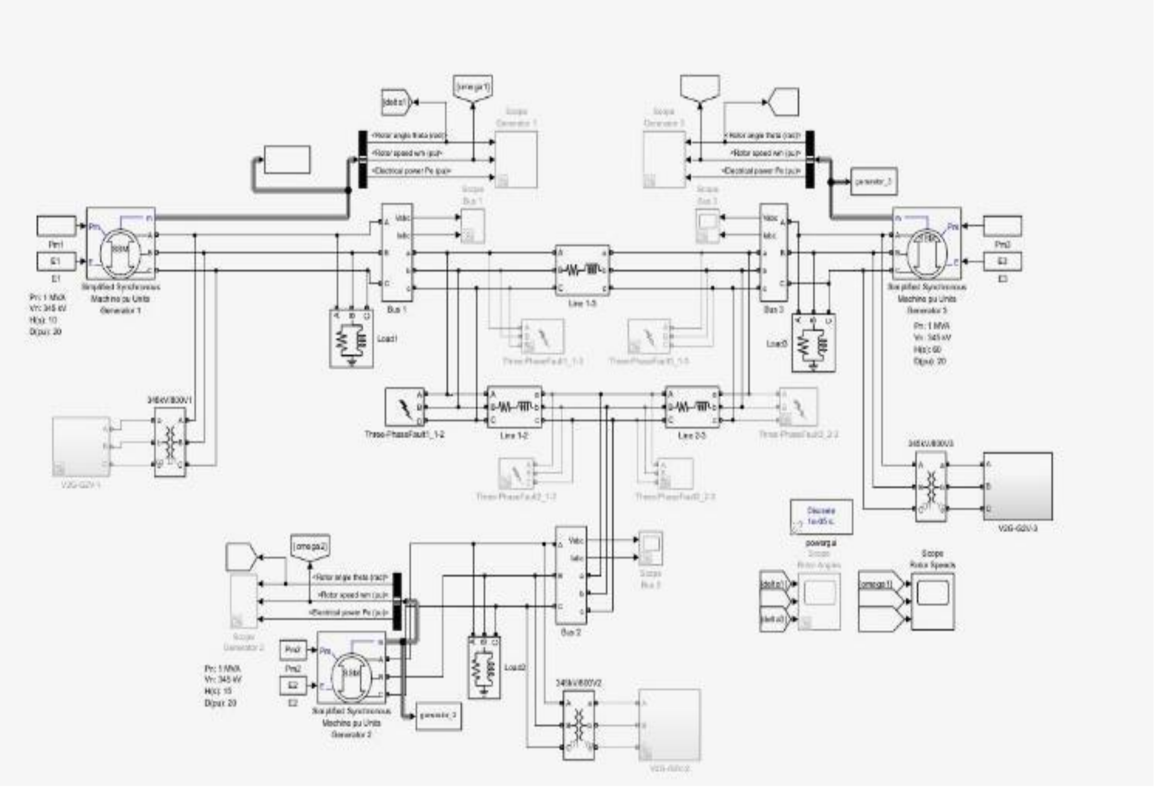
4.2 MATLAB Overview:

MATLAB (Matrix Laboratory) is a high-level programming environment designed for technical computing. It integrates computation, visualization, and programming in a user-friendly interface. Common applications include:

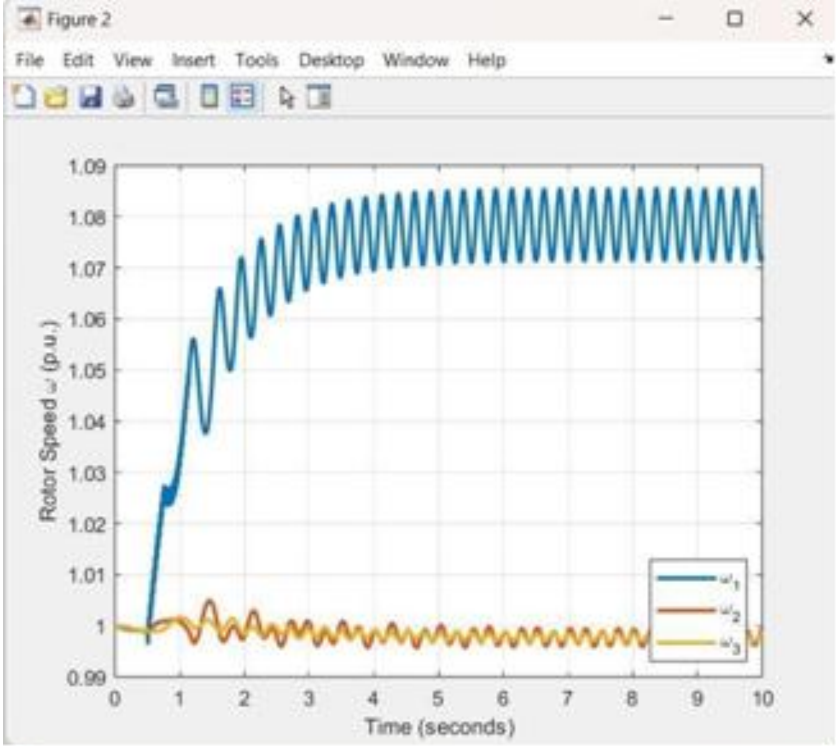
- Mathematical computation
- Algorithm development
- Data acquisition
- Modeling, simulation, and prototyping
- Data analysis and visualization
- Scientific and engineering graphics
- Application development, including GUI design

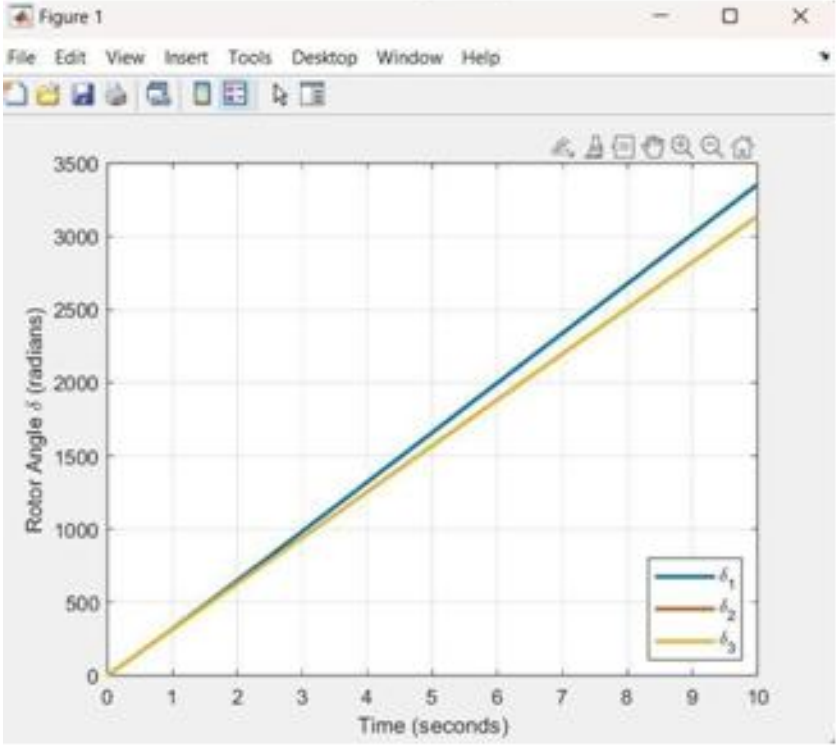
MATLAB uses matrices as its fundamental data structure, enabling efficient problem-solving for complex engineering systems. It is widely used in academia and industry for research, development, and system analysis. Toolboxes extend MATLAB's capabilities into specialized domains such as control systems, signal processing, neural networks, fuzzy logic, and simulation.

5. Simulation Circuit Diagram:



6. Output:





7. Conclusion:

The development of the Intelligent Adaptive Energy Management System (I-AEMS) for a standalone electric vehicle successfully demonstrates the effectiveness of integrating smart control strategies with real-time data analytics to enhance EV performance, efficiency, and battery longevity. By implementing dynamic power flow optimization, the system efficiently balances energy demands between propulsion, auxiliary loads, and storage components, ensuring stable operation under varying driving and environmental conditions.

The adaptive control algorithm responds effectively to load and state-of-charge variations, enabling intelligent energy distribution while preventing stress on critical components. Battery protection mechanisms including overcharge and discharge prevention enhance reliability and extend battery life. Simulation and hardware results confirm improvements in energy utilization, system stability, and drive train efficiency compared to conventional approaches. The modular design also allows integration with future technologies such as renewable energy interfaces and predictive control systems. Overall, this work demonstrates that intelligent adaptive energy management is a practical and impactful solution for next-generation electric vehicles.

8. Future Scope:

- Integration of machine learning and deep learning models (CNN/LSTM) for predictive energy optimization.
- Implementation of advanced battery health monitoring and predictive maintenance systems.
- Expansion to multi-source hybrid energy systems with smart grid connectivity.
- Real-time IoT-based monitoring and remote control capabilities.
- Large-scale deployment in smart transportation and renewable-integrated EV ecosystems.

References:

1. P. Du et al., “Real-Time Energy Management for Net-Zero Power Systems Based on Shared Energy Storage,” Journal of Modern Power Systems and Clean Energy, 2024.
2. G. S. Asha Rani et al., “Data-Driven Energy Management of an EV Charging Station Using Deep Reinforcement Learning,” IEEE Access, 2024.
3. H. Youssef et al., “Demand Side Optimization for Smart Home Energy Management,” IEEE Access, 2024.
4. M. Yavuz and Ö. C. Kivanç, “Cluster-Based EMS Using DRL and V2X,” IEEE Access, 2024.
5. P. Horrillo-Quintero et al., “Fuzzy Logic EMS for Multi-Energy Microgrid,” IEEE Access, 2024.
6. M. Aatabe et al., “Stochastic EMS for Autonomous PV Microgrid,” IEEE Access, 2024.