MSW MANAGEMENT -Multidisciplinary, Scientific Work and Management Journal
ISSN: 1053-7899
Vol. 36 Issue 2, 2026, Pages 1179-1184

AI-Driven Adaptive Power Management for Hybrid Power Plants with Battery Energy Storage System

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Abstract
This project presents an intelligent power management system for a hybrid solar–wind energy plant integrated with a Battery Energy Storage System (BESS). Renewable energy generated from solar panels and wind turbines is used to charge the battery while a Battery Management System (BMS) continuously supervises charging conditions. To ensure battery safety, the charging process is automatically disconnected during overcharging or abnormal operating conditions. The stored energy is supplied to connected electrical loads through an AI-based adaptive controller that monitors voltage, current, and load behaviour in real time. Whenever nsafe conditions such as overload, abnormal current flow, or voltage fluctuations are detected, the controller isolates the load and activates a buzzer alert to prevent system damage and improve operational safety. The proposed system applies Artificial Intelligence techniques for efficient energy coordination between renewable sources, battery storage, and load demand. By analysing generation patterns, battery state-of-charge, and consumption requirements, the controller dynamically manages charging and discharging operations to improve energy utilization and reduce power instability. The proposed approach offers a cost-effective and sustainable solution for smart renewable energy systems and future hybrid power plant applications.
Keywords: Hybrid Renewable Energy system, Battery Energy Storage System (BESS),Smart Grid Application, Real-Time monitoring, Battery Management System, Smart Hybrid power plant, solar energy, wind energy, energy storage, AI-driven grid management, Internet of Energy, sustainable power.

1. INTRODUCTION

The rapid growth in global energy demand and the increasing environmental concerns associated with conventional fossil-fuel-based power generation have accelerated the adoption of renewable energy resources such as solar and wind power. Hybrid power plants, which combine multiple energy generation sources with advanced energy storage technologies, have emerged as an effective solution for improving energy reliability, sustainability, and efficiency. However, the intermittent and unpredictable nature of renewable energy sources creates significant challenges in maintaining power quality, grid stability, and continuous energy supply. Battery Energy Storage Systems (BESS) play a crucial role in addressing these challenges by storing excess generated energy and supplying power during periods of low renewable generation or peak demand. The integration of BESS into hybrid power plants enhances system flexibility, supports load balancing, reduces energy fluctuations, and improves overall operational performance. Despite these advantages, managing the coordination between renewable energy sources, storage systems, and varying load demands remains a complex task, especially under
dynamic operating conditions. Traditional energy management approaches are often based on fixed rule-based strategies that may not effectively adapt to real-time variations in weather conditions, load patterns, and battery status. As hybrid energy systems become more complex, there is a growing need for intelligent and adaptive power management techniques capable of making fast and accurate operational decisions. Artificial Intelligence (AI), particularly machine learning, deep learning, and predictive analytics, has shown significant potential in optimizing energy systems through data-driven decision-making and real-time control. AI-driven adaptive power management systems can continuously monitor system parameters, forecast energy generation and demand, and optimize the charging and discharging operations of the Battery Energy Storage System. These intelligent systems improve energy efficiency, reduce operational costs, enhance battery lifespan, and ensure stable power delivery. Furthermore, AI-based control strategies can support advanced functionalities such as fault detection, predictive maintenance, peak load management, and demand response operations within smart grid environments.
This study focuses on the development of an AI-driven adaptive power management framework for hybrid power plants integrated with Battery Energy Storage Systems. The proposed approach aims to optimize energy flow among renewable sources, storage systems, and electrical loads by utilizing intelligent control

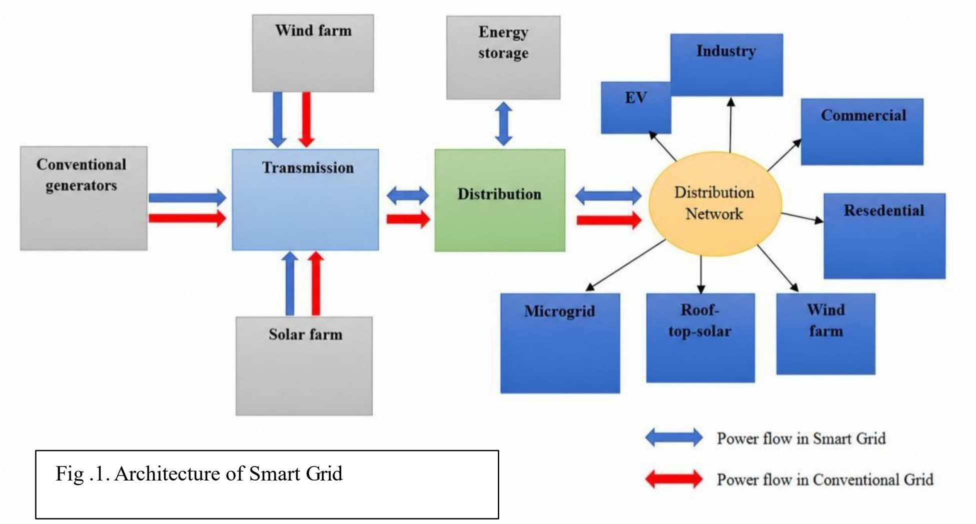

Fig .1. Architecture of Smart Grid

algorithms and real-time data analysis. The research investigates how AI techniques can improve system reliability, maximize renewable energy utilization, and support sustainable energy management in future power systems. The remainder of this work discusses the system architecture, AI-based control methodologies, operational strategies of the Battery Energy Storage System, simulation analysis, and performance evaluation of the proposed adaptive power management framework.

The given diagram represents the architecture and power flow operation of a Smart Grid system integrated with renewable energy sources, energy storage, and various consumer sectors. The system combines conventional power generation with modern renewable energy technologies to ensure reliable, efficient, and sustainable electricity distribution. In the left section of the diagram, conventional generators act as the primary power source, supplying electricity to the transmission system. Along with conventional generation, renewable energy sources such as wind farms and solar farms are also connected to the transmission network. These renewable sources help reduce dependency on fossil fuels and support clean energy generation. The transmission system transfers electrical energy over long distances and sends it to the distribution system for further delivery to end users. An energy storage system is also connected to the distribution side to store excess energy generated during peak renewable production and supply it back when demand increases or renewable generation decreases.
The distribution network acts as the central hub of the smart grid and connects multiple sectors such as industries, commercial buildings, residential areas, electric vehicles (EVs), microgrids, rooftop solar systems, and additional wind farms. Unlike conventional grids, where electricity flows only in one direction, the smart grid supports bidirectional power flow, allowing consumers to both consume and generate electricity. For example, rooftop solar systems and microgrids can send excess energy back to the distribution network. The blue arrows in the diagram represent power flow in a smart grid, while the red arrows indicate conventional one-way power flow. Smart grids use advanced communication systems, sensors, automation, and intelligent controllers to monitor power generation, consumption, and distribution in real time. This improves energy efficiency, reduces power losses, enhances grid stability, and supports better integration of renewable energy sources.

2.1 Working Principle of Hybrid Power Plant

An AI-driven adaptive power management system in a hybrid power plant works by intelligently coordinating renewable energy sources such as solar panels and wind turbines together with a Battery Energy Storage System (BESS) to ensure continuous, stable, and efficient power supply. The system continuously monitors important parameters including power generation, battery condition, load demand, voltage, current, frequency, and weather conditions using sensors and smart controllers. Renewable energy produced from solar and wind sources is first supplied directly to the electrical load, while excess generated energy is stored in the battery system for future use. During periods of low renewable energy generation or sudden increases in load demand, the stored energy in the battery is automatically discharged to maintain uninterrupted power delivery. The Battery Management System (BMS) plays a critical role in supervising battery health, temperature, state of charge, charging cycles, and safety conditions to prevent overcharging, deep discharge, overheating, and short circuits. If any abnormal condition occurs, protection circuits automatically isolate the faulty section to ensure system safety and reliability.
Artificial Intelligence algorithms continuously analyze real-time and historical data to predict future energy generation and consumption patterns. Based on these predictions, the AI controller makes adaptive decisions such as switching between energy sources, optimizing battery charging and discharging operations, balancing load demand, minimizing energy losses, and improving overall system efficiency. The controller prioritizes renewable energy utilization to reduce dependency on conventional backup sources and supports sustainable energy management. In smart grid applications, the system can also communicate with connected loads and grid infrastructure through intelligent communication networks to support demand response, remote monitoring, load scheduling, and energy sharing. By combining renewable energy integration, intelligent battery control, predictive AI algorithms, real-time monitoring, and automated protection mechanisms, the system provides reliable, efficient, cost-effective, and environmentally sustainable power management for modern hybrid power plants.

2.2 Overview of Hybrid Power Plant Architecture

Hybrid power plants are modern energy systems that combine two or more power generation sources along with energy storage technologies to produce reliable, efficient, and continuous electricity. These systems commonly integrate renewable energy sources such as solar photovoltaic (PV) panels and wind turbines with conventional power generators and Battery Energy Storage Systems (BESS). The primary objective of a hybrid power plant is to overcome the limitations of individual energy sources and ensure stable power supply under varying environmental and load conditions. By combining multiple energy sources, hybrid power plants improve energy reliability, reduce dependency on fossil fuels, and support sustainable power generation. Renewable energy sources such as solar and wind are naturally intermittent because their power generation depends on weather conditions. Solar power output decreases during cloudy weather or nighttime, while wind energy generation varies according to wind speed. To maintain uninterrupted electricity supply and system stability, hybrid power plants utilize Battery Energy Storage Systems to store excess energy generated during periods of high renewable energy production. The stored energy is later used when renewable generation becomes insufficient or when load demand increases. This combination of renewable energy and storage systems helps balance power generation and consumption effectively.A typical hybrid power plant consists of solar panels, wind turbines, battery storage units, power electronic converters, control systems, smart sensors, and an Energy Management System (EMS). The Energy Management System continuously monitors power generation, battery status, and load demand to optimize energy distribution and improve operational efficiency. In modern hybrid power plants, Artificial Intelligence (AI) technologies are increasingly integrated to enhance forecasting, decision-making, and adaptive control. AI algorithms analyze real-time and historical data to predict energy generation, weather conditions, and consumption patterns, enabling intelligent energy management and reduced energy losses. The working principle of a hybrid power plant involves balancing power generation and electricity consumption in real time. During periods of high renewable energy generation, surplus electricity is stored in the battery system for future use. When renewable energy production decreases or electricity demand increases, the stored battery energy is automatically discharged to support the electrical load. If both renewable generation and battery capacity become insufficient, backup generators or grid power are used to maintain continuous electricity supply. Overall, hybrid power plants provide a reliable, efficient, environmentally friendly, and cost-effective solution for modern power generation by integrating renewable energy sources, energy storage systems, and intelligent energy management technologies.
The overall power balance in a hybrid power plant can be represented as: Where:

- Power generated by solar panels
- Power generated by wind turbines
- Battery charging or discharging power
- Power supplied from the grid or backup generator
- Total load demand
- System losses

Hybrid power plants offer significant advantages over traditional power generation systems by combining multiple energy sources with advanced energy storage and intelligent control technologies. One of the major benefits of hybrid power plants is improved energy reliability and continuity of power supply. Traditional power systems often depend heavily on a single energy source, which may lead to power interruptions during fuel shortages, equipment failures, or environmental changes. In contrast, hybrid power plants integrate renewable energy sources such as solar and wind with Battery Energy Storage Systems (BESS) and backup generators, ensuring stable and uninterrupted electricity generation even under varying environmental and load conditions. This makes hybrid systems highly suitable for modern energy requirements where reliability and efficiency are critical.
Another important advantage of hybrid power plants is the reduction in dependence on fossil fuels and conventional thermal power generation. Renewable energy sources such as solar and wind produce clean electricity without emitting harmful greenhouse gases or pollutants. By increasing the use of renewable energy, hybrid systems contribute to environmental sustainability and help reduce carbon emissions responsible for climate change and global warming. In addition, hybrid power plants support better energy utilization by efficiently balancing renewable generation and load demand through intelligent energy management systems. Excess renewable energy generated during peak production periods can be stored in battery systems and used later during low generation periods, reducing energy wastage and improving overall system efficiency.The inclusion of Battery Energy Storage Systems (BESS) plays a vital role in enhancing the performance and stability of hybrid power plants. BESS helps maintain voltage stability and frequency regulation by instantly supplying or absorbing power according to system demand. It also supports peak load management by delivering stored energy during periods of high electricity demand, thereby reducing stress on the grid and improving power quality. Battery systems further improve system reliability during sudden fluctuations in renewable energy generation caused by changing weather conditions. In addition to energy storage, modern hybrid power plants increasingly utilize Artificial Intelligence (AI) and adaptive control technologies to improve operational efficiency. AI algorithms analyze real-time and historical data related to weather conditions, renewable energy generation, battery status, and load demand. Based on these analyses, the AI controller can forecast future energy production and consumption patterns, optimize battery charging and discharging cycles, minimize energy losses, and improve overall power management in real time.
Hybrid power plants are widely used in various applications due to their flexibility, efficiency, and sustainability. They are commonly implemented in smart grid

MSW MANAGEMENT -Multidisciplinary, Scientific Work and Management Journal
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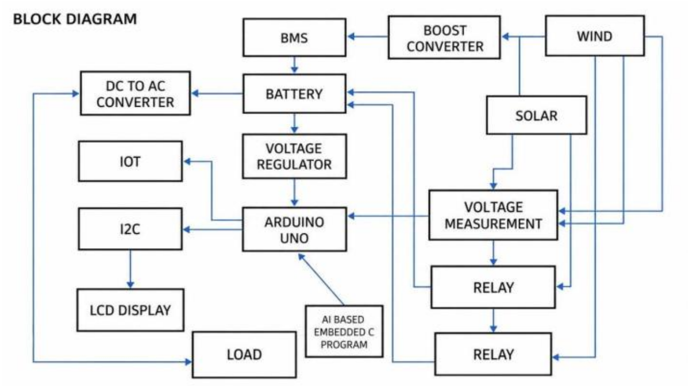
Vol. 36 Issue 2, 2026, Pages 1179-1184

systems where intelligent energy management and bidirectional power flow are essential. In remote villages and rural areas where grid connectivity is limited or unavailable, hybrid power plants provide reliable electricity using locally available renewable resources. These systems are also highly beneficial for industrial facilities that require continuous and stable power for manufacturing operations. Island power systems, which often face challenges related to fuel transportation and limited energy resources, use hybrid plants to improve energy independence and reduce operational costs. Furthermore, hybrid power systems are increasingly being deployed in electric vehicle (EV) charging stations to support clean transportation infrastructure using renewable energy and battery storage. As the global demand for clean, reliable, and sustainable energy continues to grow, hybrid power plants integrated with AI and BESS are becoming a key component of future energy infrastructure. Their ability to combine renewable energy generation, intelligent energy management, and advanced storage technologies makes them an effective solution for addressing modern energy challenges. With continuous advancements in battery technology, smart grids, and artificial intelligence, hybrid power plants are expected to play a major role in achieving energy sustainability, reducing environmental impact, and supporting the transition toward a greener and smarter energy future.

3 Materials and Methods

The given block diagram represents an AI-driven adaptive hybrid power management system that integrates renewable energy sources such as solar and wind



energy with a Battery Energy Storage System (BESS), intelligent controllers, IoT communication, and automated load management. The system is designed to ensure efficient, reliable, and continuous power supply by combining renewable energy generation, battery storage, real-time monitoring, and Artificial Intelligence-based decision-making. The major components included in the system are solar panels, wind energy system, boost converter, Battery Management System (BMS), battery, voltage regulator, Arduino Uno controller, relays, IoT module, I2C communication module, LCD display, DC to AC converter, voltage measurement unit, and load section. The operation of the system begins with renewable energy generation through solar panels and wind turbines. The solar module converts sunlight into electrical energy, while the wind energy system generates electricity using wind power. Since renewable energy sources produce variable output depending on weather conditions, the generated power is regulated and controlled before being supplied to the load or battery system. The wind energy output is connected to a boost converter, which increases and stabilizes the voltage level to meet system requirements. The generated renewable energy is continuously monitored through the voltage measurement unit, which measures voltage levels and sends the data to the Arduino Uno controller for analysis and control operations.The Battery Energy Storage System plays a major role in maintaining uninterrupted power supply. The battery stores excess energy generated from solar and wind sources during high production periods. When renewable generation decreases or load demand increases, the stored battery energy is discharged to support the electrical load. The Battery Management System (BMS) supervises battery charging and discharging operations, battery temperature, voltage, current, and state of charge to ensure safe and efficient battery performance. The BMS protects the battery from overcharging, deep discharge, overheating, and short circuits, thereby improving battery lifespan and system reliability.The voltage regulator provides stable voltage supply to the Arduino Uno controller and other low-voltage electronic components. The Arduino Uno acts as the central control unit of the entire system. It receives input data from the voltage measurement unit, battery system, sensors, and AI-based embedded control program. Based on the collected data, the controller makes intelligent decisions regarding energy flow, battery charging and discharging, relay switching operations, and load management. The AI-based embedded C program enhances system intelligence by analyzing real-time data and adapting system operation according to changing power generation and load conditions.The relay modules are used for automatic switching and control of power sources and electrical loads. Depending on renewable energy availability, battery condition, and load demand, the controller activates or deactivates relays to manage power distribution efficiently. The DC to AC converter converts stored DC power from the battery into AC power suitable for operating household or industrial electrical loads. This enables the system to supply standard AC electricity to connected devices and appliances.

The IoT module enables remote monitoring and smart communication capabilities within the hybrid power management system. Through IoT technology, system parameters such as voltage, current, battery status, power consumption, and renewable energy generation can be monitored remotely using internet-based platforms. The I2C communication module is used to establish communication between the Arduino Uno and the LCD display. The LCD display provides real-time information regarding system status, battery condition, voltage levels, energy source operation, and load status for users and operators.

Overall, the AI-driven adaptive hybrid power management system combines renewable energy integration, intelligent control, battery storage, IoT communication, and automated protection mechanisms to provide efficient and sustainable energy management. The use of Artificial Intelligence improves system adaptability, energy optimization, and decision-making capability. This type of system is highly suitable for smart grids, industrial power systems, remote areas, electric vehicle charging stations, and sustainable energy applications where reliable and intelligent power management is essential.

3.1 **Battery Management System (BMS)** The Battery Management System (BMS) is one of the most important components in an AI-driven adaptive hybrid power management system. It is responsible for monitoring, protecting, and controlling the operation of the battery pack used for energy storage. The BMS continuously observes important battery parameters such as voltage, current, temperature, charging status, discharging condition, and State of Charge (SOC). By constantly monitoring these parameters, the system ensures that the battery operates within safe limits and maintains optimal performance. Since batteries are sensitive to abnormal operating conditions, the BMS plays a critical role in preventing damage and improving battery lifespan.

One of the major functions of the BMS is to protect the battery from overcharging and deep discharging. Overcharging can increase battery temperature and damage internal battery cells, while deep discharge can reduce battery efficiency and shorten battery life. The BMS automatically controls charging and discharging operations to avoid such conditions. It also protects the system from overheating, short circuits, and excessive current flow by disconnecting the battery during unsafe operating conditions. In addition, the BMS balances the voltage levels of individual battery cells to ensure uniform charging and stable operation.

In an AI-driven adaptive power management system, the BMS provides real-time battery information to the central controller, such as the Arduino Uno or AI processor. The AI algorithm analyzes battery data and makes intelligent decisions regarding energy storage, charging cycles, load balancing, and power distribution. This improves energy efficiency and enables predictive battery management. The BMS also contributes to system reliability by ensuring uninterrupted power supply during renewable energy fluctuations and varying load conditions. Overall, the Battery Management System enhances battery safety, operational efficiency, system stability, and energy management performance in the hybrid power plant.

3.2 **Battery:** The battery acts as the primary energy storage unit in the hybrid power plant and plays a vital role in maintaining continuous power supply. Renewable energy sources such as solar panels and wind turbines generate electricity depending on environmental conditions, which may vary throughout the day. To overcome these fluctuations and maintain stable energy delivery, the battery stores excess electrical energy generated during periods of high renewable energy production. The stored energy is later used when renewable generation becomes insufficient or when load demand increases.

The integration of battery energy storage improves system stability, reliability, and flexibility. During daytime or high wind conditions, excess electricity generated from solar and wind systems is directed to charge the battery. During nighttime, cloudy weather, or low wind conditions, the battery automatically discharges stored energy to support the electrical load. This ensures uninterrupted power supply and reduces dependency on backup generators or conventional grid power. The battery also helps in reducing power fluctuations, voltage instability, and sudden load variations within the hybrid system.

In AI-driven adaptive power management systems, the battery operation is intelligently controlled based on real-time energy generation and consumption patterns. Artificial Intelligence algorithms analyze battery condition, charging status, renewable energy availability, and load demand to optimize charging and discharging cycles. This improves battery efficiency, extends battery lifespan, and reduces unnecessary energy losses. Batteries used in hybrid systems are commonly lithium-ion, lead-acid, or advanced storage technologies depending on system requirements. Overall, the battery serves as a reliable backup power source and enhances the performance and sustainability of the hybrid power plant.

3.3 **Boost Converter:** The boost converter is a DC-DC power electronic converter used in the hybrid power plant to increase and stabilize the voltage level generated from renewable energy sources such as solar panels and wind turbines. Renewable energy sources often produce variable output voltages depending on environmental conditions like sunlight intensity and wind speed. Since these voltage levels may not always match the required system operating voltage, the boost converter raises the input voltage to a higher and stable level suitable for battery charging, power distribution, and load operation.

The boost converter operates by storing electrical energy temporarily in inductors and releasing it at a higher voltage through switching operations controlled by semiconductor devices such as transistors and diodes. This voltage conversion process improves power transfer efficiency and ensures stable energy flow within the hybrid power system. By regulating the voltage output, the boost converter helps maintain consistent system performance even during fluctuations in renewable energy generation.In an AI-driven adaptive power management system, the boost converter operates dynamically according to real-time energy conditions and load requirements. The AI controller continuously monitors renewable energy availability, battery condition, and load demand to adjust converter operation for maximum efficiency. This adaptive control reduces energy losses and optimizes battery charging performance. The boost converter also protects connected components from voltage instability and improves the overall reliability of the power system. Therefore, it plays a critical role in efficient renewable energy integration and power management.

3.4 **Wind Energy System:** The wind energy subsystem is an important renewable energy source in the hybrid power plant. It converts the kinetic energy of moving wind into electrical energy using wind turbines and electrical generators. Wind energy is considered a clean, renewable, and environmentally friendly source of electricity because it does not produce greenhouse gas emissions or harmful pollutants during operation. The wind turbine captures wind energy through rotating blades, which drive a generator to produce electrical power.The amount of electricity generated by the wind subsystem depends on wind speed, turbine design, and environmental conditions. Since wind speed varies continuously, wind energy generation is intermittent and unpredictable. Therefore, adaptive power management is necessary to maintain stable and efficient system operation. The generated electrical energy is regulated using power electronic converters and supplied either directly to the load or to the battery storage system for future use.In AI-driven hybrid power plants, Artificial Intelligence algorithms help forecast wind energy availability using weather data, historical wind patterns, and real-time sensor measurements. The AI controller uses these predictions to optimize energy allocation between the wind system, solar system, battery storage, and electrical loads. This improves renewable energy utilization and reduces energy wastage. Wind energy systems are widely used in hybrid power plants because they complement solar energy generation, especially during nighttime or cloudy weather conditions. Overall, the wind subsystem contributes significantly to sustainable and reliable power generation.

3.5 **Solar Energy System:** The solar subsystem generates electrical energy by converting sunlight into electricity using photovoltaic (PV) panels. Solar energy is one of the most widely used renewable energy sources because it is clean, abundant, sustainable, and environmentally friendly. The photovoltaic panels consist of semiconductor materials that produce electrical current when exposed to sunlight through the photovoltaic effect. The generated DC power is then regulated and utilized within the hybrid power system. The output power from solar panels depends on factors such as sunlight intensity, panel orientation, temperature, shading, and weather conditions. During sunny periods, the solar subsystem generates sufficient electricity to supply the load and charge the battery storage system. However, solar generation decreases during cloudy weather or nighttime. Therefore, energy storage systems and adaptive power management are essential to ensure uninterrupted power supply. In an AI-driven adaptive hybrid power plant, Artificial Intelligence techniques are used to predict solar energy generation based on weather forecasting and real-time environmental data. The AI controller analyzes solar power availability and intelligently manages power distribution between the battery, load, and other renewable sources. This improves energy efficiency and reduces dependency on conventional backup systems. Solar energy systems are widely adopted because of their low operating cost, minimal maintenance requirements, and environmental benefits. Overall, the solar subsystem plays a major role in achieving sustainable and reliable energy generation in hybrid power plants.

3.6 **Voltage Measurement Unit:** The voltage measurement unit is responsible for continuously monitoring voltage levels throughout different sections of the hybrid power system. It measures the voltage generated from solar panels, wind turbines, battery systems, converters, and load terminals. Accurate voltage monitoring is essential for maintaining stable operation, protecting system components, and ensuring efficient energy management within the hybrid power plant. The measured voltage data is transmitted to the Arduino Uno or central controller for analysis and decision-making. If abnormal voltage conditions such as overvoltage or undervoltage occur, the controller can take corrective actions such as adjusting converter operation, switching relays, or disconnecting faulty sections. This helps protect electrical equipment and improves overall system reliability.

In AI-based adaptive systems, voltage measurements are continuously analyzed using intelligent algorithms to optimize energy flow and maintain system efficiency. The AI controller uses voltage information to balance power generation, battery charging, and load demand dynamically. Real-time voltage monitoring also helps reduce power fluctuations and improve energy quality. Therefore, the voltage measurement unit is an essential component for safe and efficient operation of the hybrid power management system.

3.7 **Relay:** Relays are electrically operated switches used to control the connection and disconnection of electrical circuits within the hybrid power plant. They are essential for managing power flow between renewable energy sources, battery storage systems, converters, and electrical loads. Relays provide electrical isolation and protection by automatically switching circuits based on control signals from the Arduino Uno or central controller.

In the hybrid power management system, relays help control the operation of solar panels, wind systems, battery charging, load connection, and backup power sources. Depending on energy availability and system conditions, the controller activates or deactivates relays to optimize power distribution and maintain system stability. For example, if renewable energy generation becomes insufficient, the relay can switch the load to battery power or backup generation automatically.

In AI-driven systems, relay operations are intelligently controlled using real-time data and predictive analysis. Artificial Intelligence algorithms analyze renewable energy generation, battery condition, and load demand to make adaptive switching decisions. This improves energy efficiency, reduces unnecessary switching operations, and enhances system reliability. Overall, relays play a critical role in automated power management and protection within the hybrid power plant.

3.8 **Voltage Regulator:** The voltage regulator is used to maintain a stable and constant voltage supply for sensitive electronic components within the hybrid power management system. Renewable energy sources and batteries often produce fluctuating voltage levels due to varying environmental and operating conditions. The voltage regulator ensures that electronic devices such as the Arduino Uno, sensors, communication modules, and control circuits receive the required operating voltage. Stable voltage supply is essential for accurate monitoring, reliable control operation, and system safety. If voltage fluctuations are not properly regulated, sensitive electronic components may malfunction or become damaged. The voltage regulator protects the system by eliminating voltage variations and providing consistent power output.In the hybrid power plant, the voltage regulator supports stable operation of the control and communication systems. It improves system reliability and ensures uninterrupted functioning of sensors, IoT modules, displays, and controllers. In AI-driven systems, stable voltage supply is especially important because intelligent decision-making and adaptive control depend on accurate sensor readings and reliable controller performance. Therefore, the voltage regulator plays an important role in maintaining safe and efficient system operation.

3.9 **Arduino Uno:**The Arduino Uno serves as the main control unit of the AI-driven adaptive hybrid power management system. It coordinates the operation of sensors, relays, converters, communication modules, and energy sources within the hybrid plant. The Arduino Uno is a microcontroller-based development board widely used for embedded systems, automation, and intelligent control applications because of its simplicity, flexibility, low cost, and ease of programming.

3.10 AI-Based Embedded C Program : The AI-based embedded C program is designed to implement intelligent decision-making and adaptive power management within the hybrid energy system. The program analyzes real-time data from sensors and renewable energy sources to optimize battery charging, load distribution, and source selection. By using AI techniques, the system can predict energy availability, reduce power losses, and improve overall efficiency. The

MSW MANAGEMENT -Multidisciplinary, Scientific Work and Management Journal
ISSN: 1053-7899
Vol. 36 Issue 2, 2026, Pages 1179-1184

embedded program enables automated operation and enhances the reliability of the hybrid power plant.

3.11 Overall System Working: The AI-Driven Adaptive Power Management System for Hybrid Power Plants integrates solar, wind, and battery energy storage to provide reliable and efficient power generation. Renewable energy sources generate electricity, which is regulated, monitored, and stored in the battery through intelligent control mechanisms. The Arduino Uno and AI-based embedded program continuously analyze system conditions and manage energy distribution using relays, sensors, and communication modules. The system ensures optimal utilization of renewable energy, reduces power wastage, improves battery life, and provides a stable power supply to the load through adaptive and automated operation.

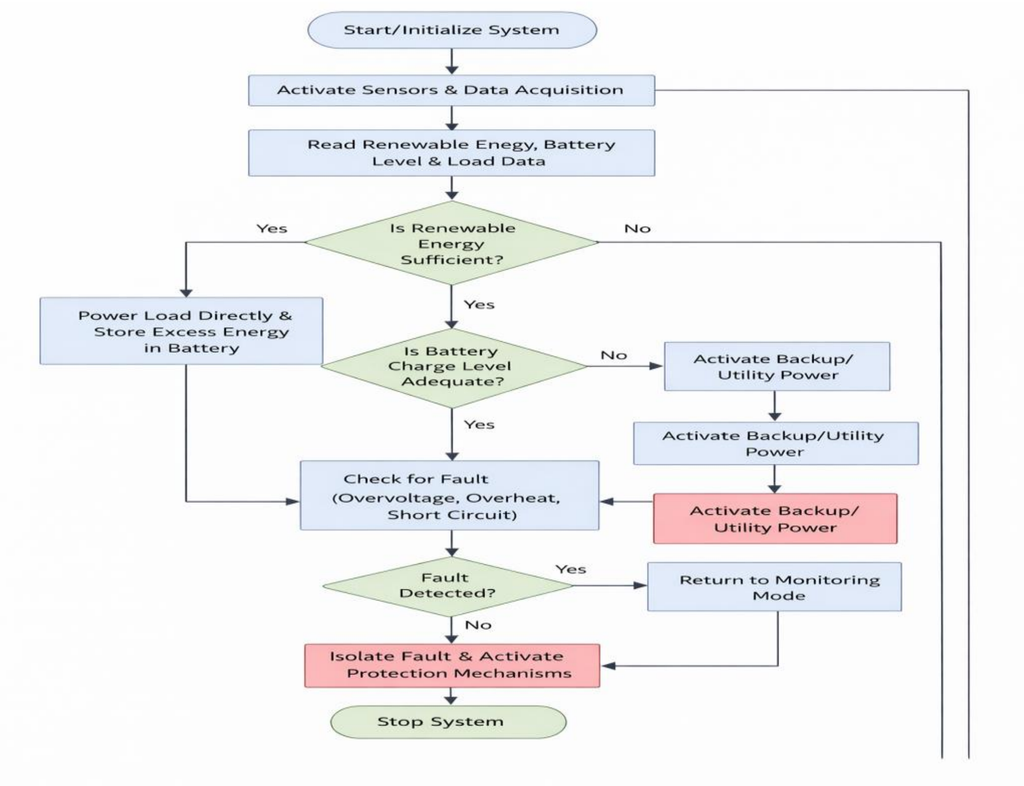
4 .Software Design and Embedded Programming

4.1 Embedded C Programming: Embedded C programming is used for developing the control logic of the hybrid power management system. It enables the Arduino Uno microcontroller to interact with sensors, relays, converters, communication modules, and display units. The Embedded C program continuously reads input data such as voltage levels, battery status, renewable energy generation, and load demand through analog and digital interfaces. Based on predefined control algorithms and AI-based decision-making logic, the controller manages battery charging and discharging operations, relay switching, and power distribution between solar, wind, battery, and load sections. The embedded program also includes protection mechanisms to prevent unsafe operating conditions such as overvoltage, undervoltage, battery overcharging, deep discharge, and short circuits. Timer functions, interrupt handling, serial communication, and sensor interfacing are implemented within the Embedded C code to ensure smooth and real-time system operation. The flexibility and efficiency of Embedded C make it suitable for low-power, real-time energy management applications.

4.2 Data Acquisition and Processing: Data acquisition is an important part of the hybrid power management system because it enables real-time monitoring and intelligent control. Sensors and voltage measurement units continuously collect data related to voltage, current, battery status, renewable energy generation, and load conditions. This xdata is transmitted to the Arduino Uno controller through analog and digital input channels.The acquired data is processed using embedded software and AI algorithms to identify system conditions and make adaptive control decisions. Signal filtering and calibration techniques are applied to improve measurement accuracy and reduce noise. Processed data is used for battery management, relay control, energy optimization, and fault detection. Continuous data acquisition and processing improve system reliability, efficiency, and real-time responsiveness

4.3 IoT Dashboard and Monitoring: The Internet of Things (IoT) module enables remote monitoring and smart communication within the hybrid power management system. Real-time system parameters such as battery voltage, renewable energy generation, load consumption, and system status are transmitted to cloud platforms or IoT dashboards through wireless communication technologies. The IoT dashboard provides graphical visualization of system performance, enabling users and operators to monitor energy generation, battery condition, and load demand remotely using smartphones, tablets, or computers. Alerts and notifications can also be generated when abnormal conditions occur, such as battery overheating or voltage fluctuations. IoT-based monitoring improves system accessibility, automation, predictive maintenance, and remote control capabilities in smart energy applications. The embedded code is compiled using the Arduino IDE compiler, and any syntax or logic errors are corrected before uploading the program to the microcontroller. Serial monitor functionality within the IDE is also used for debugging and monitoring real-time system parameters during testing. The Arduino IDE simplifies the implementation process and supports rapid development of intelligent embedded applications for hybrid power management systems.

4.4 Control Logic Flowchart: The control logic flowchart represents the operational sequence and decision-making process of the hybrid power management system. The flowchart begins with system initialization, sensor activation, and data acquisition from renewable energy sources, battery systems, and load units. The controller continuously checks renewable energy availability, battery charge level, and load demand. Based on the collected data, the AI algorithm determines the appropriate operating mode. If renewable energy generation is sufficient, the load is powered directly and excess energy is stored in the battery. If renewable generation becomes insufficient, the controller activates battery discharge mode to maintain uninterrupted power supply. Relays are automatically switched according to system conditions to manage power flow efficiently. Protection mechanisms are also included in the flowchart to handle abnormal conditions such as overvoltage, battery overheating, and short circuits. The control logic flowchart helps visualize system operation and simplifies software implementation



Control Logic Flowchart Demenstrotion Hydrid Power Piant

Conclusion

This study presented an AI-driven adaptive power management system for hybrid solar–wind power plants integrated with a Battery Energy Storage System (BESS). The proposed system intelligently manages energy generation, storage, and load distribution by continuously monitoring voltage, current, battery status, and load conditions. The AI-based controller improves system efficiency, enhances power stability, and ensures safe operation through automatic fault detection and

MSW MANAGEMENT -Multidisciplinary, Scientific Work and Management Journal
ISSN: 1053-7899
Vol. 36 Issue 2, 2026, Pages 1179-1184

protection mechanisms. In abnormal conditions such as overcharging or load-side faults, the system disconnects the power supply and activates an alert system to prevent damage. The integration of renewable energy sources with intelligent battery management reduces energy wastage, improves reliability, and extends battery lifespan. Overall, the proposed framework provides a sustainable, reliable, and cost-effective solution for future smart grid and renewable energy applications.

In conclusion, the AI-Driven Adaptive Power Management System for Hybrid Power Plants with Battery Energy Storage System offers a smart, reliable, economical, and eco-friendly solution for future energy systems. The combination of renewable energy integration, AI-based automation, battery storage technology, and IoT-enabled monitoring creates a highly efficient energy management platform suitable for residential, commercial, industrial, and smart grid applications. The proposed system not only enhances energy efficiency and power quality but also supports the global transition toward sustainable and intelligent energy infrastructure.

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