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Energy-Efficient IoT Technologies for Sustainable Development

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Abstract: The integration of green energy solutions into smart cities, facilitated by Internet of Things (IoT) technologies, presents a promising avenue for advancing sustainable development and addressing energy challenges. This paper presents an approach for the implementation of an IoT-enabled integrated system aimed at promoting sustainable energy practices in smart cities. A relay circuit is added to improve fault management and mitigation in the renewable energy system (RES), and to reduce grid disruptions. Backup power sources like diesel generators (DG) are easily integrated into the system to assure power delivery during renewable source interruptions or high demand. An IoT control system with sensors, actuators, and a data hub allows real-time energy flow monitoring and optimization. Testing and optimization ensure component integration and operation, resulting in a robust and scalable smart energy system. Numerical results demonstrate the performance and stability of key components, validating the effectiveness of the proposed methodology in promoting sustainable energy practices in urban environments. The inverter module produces 620volt direct current (DC) voltage from the solar photovoltaic (SPV) device, stabilizing voltage and current. Diesel generator sets settle approximately 0.35 seconds, after starting voltage, current, and power oscillations. Wind turbine output stabilizes after early fluctuations. As current increases, the battery unit maintains a constant voltage range of 258.545 V to 258.565 V. Power generation, fault status, and grid branch condition are monitored in real time via the IoT device interface, enabling load distribution evaluation.

Keywords: *Energy-efficient, IoT Technologies, Sustainable Development, Renewable Energy Sources, Green Energy*

1. Introduction

The concept of sustainable development has become increasingly pivotal in an era defined by both technological advancements and growing environmental concerns [1]. Among the technologies at the forefront of merging efficiency with innovation is the Internet of Things (IoT) [2]. IoT is fundamentally transforming how people interact with the environment, manage resources, and optimize the energy consumption of countless devices interconnected across the globe [3]. As the IoT continues to expand its reach, its potential to support sustainable development goals (SDGs) becomes more significant, especially in terms of energy efficiency which is a critical aspect of environmental sustainability [4] [5].

IoT can be utilized to emissions and development by promoting efficient energy management, reducing greenhouse gas emissions, and preserving natural resources [6][7]. Energy, agriculture, and waste management are just a few of the many industries that might benefit from integrating IoT devices to increase operational efficiency, decrease waste, and make better judgments about sustainable practices [8]. Intelligent energy equipment, such smart meters and grids, may be created using IoT technology. These devices have the potential to improve energy efficiency and decrease energy usage [9] [10]. By integrating renewable energy sources into the energy landscape, IoT can contribute to the transition toward a more sustainable energy system [11]. Figure 1 shows the sustainable development in IoT technologies.

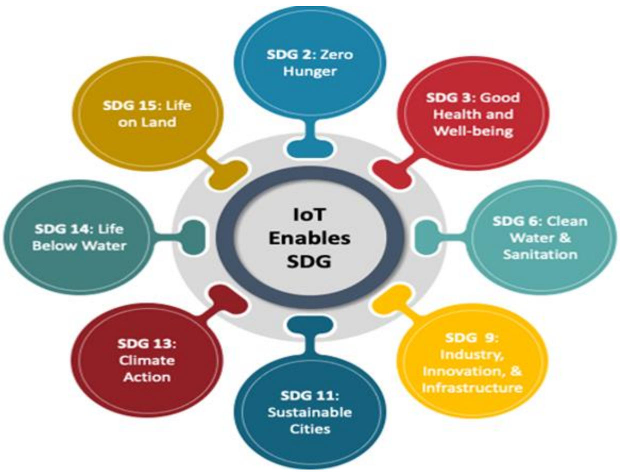

Fig 1. IoT for Sustainable Development [12]

IoT devices can be very helpful in managing trash by keeping an eye on how much is being thrown away and coming up with ways to cut down on it [13]. When it comes to air quality, IoT sensors can quickly identify dangerous pollution levels and notify people [14]. Finally, IoT devices are very helpful in sustainable agriculture for tracking things like crop development, water use, soil fertility, and insect management [15]. The data collected from these devices might help farmers and agricultural enterprises make better operational choices, which in turn would support sustainability efforts in the industry [16].

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The advent of IoT technologies offers a promising pathway towards achieving this transition by facilitating real-time monitoring, analysis, and control of energy consumption patterns [17] [18]. By embedding sensors, actuators, and communication devices into physical infrastructure and assets, IoT enables the creation of interconnected ecosystems capable of optimizing energy usage, enhancing operational efficiency, and reducing waste [19-21]. The IoT enables digitalization to change an energy system into an integrated one, moving from a one-way flow of power from generators to distribution networks to end users [22].

IoT technology has evolved from a mere concept of connectivity to a robust network of intelligent devices that collect, transmit, and process data to make smart decisions without human intervention [23]. This evolution began with the basic automation of household appliances and has expanded to include sophisticated urban and industrial systems. IoT's role in energy conservation is one of its most promising aspects for sustainable development [24]. By enabling precise control over energy consumption and providing real-time data, IoT technologies can lead to substantial reductions in unnecessary energy use, thereby reducing the carbon footprint of industries and urban areas alike [25] [26].

Energy-efficient IoT technologies integrate advanced sensors, improved connectivity, and smarter analytics to monitor and optimize energy usage in various sectors, including manufacturing, transportation, and residential areas [27]. For example, smart grids equipped with IoT technologies can dynamically respond to changes in energy demand and supply, improving efficiency and reliability while supporting the integration of renewable energy sources. In buildings, IoT can automate systems for lighting, heating, ventilation, and air conditioning significantly reducing energy waste through intelligent scheduling and occupancy sensing [28].

Despite the clear benefits, the widespread adoption of energy efficient IoT technologies faces several challenges [29]. These include the high initial costs of IoT infrastructure, concerns about data security and privacy, and the need for standardized regulations to ensure interoperability between different devices and systems. A pressing research problem in the field of energy efficient IoT technologies for sustainable development is the optimization of power consumption in IoT devices while maintaining functionality and performance. This involves addressing challenges such as enhancing energy harvesting techniques, developing efficient communication protocols, and designing low-power hardware architectures. Additionally, ensuring the security and privacy of data transmitted and processed by IoT devices amidst energy-saving measures remains a critical concern. Finding innovative solutions to these challenges is essential for maximizing the potential of IoT in contributing to sustainable development goals while minimizing its environmental impact. To overcome from these challenges this research aims to develop and implement an integrated smart energy solution for urban areas, focusing on the design, deployment, and optimization of renewable energy sources (RES) coupled with advanced IoT control systems. The contribution of this research lies in its holistic approach towards addressing energy challenges by leveraging renewable sources and IoT technologies, ensuring reliable energy supply, minimizing downtime, optimizing energy production, and enhancing grid resilience. By providing a detailed roadmap and methodology for implementing such a system, this research serves as a valuable resource for policymakers, urban planners, and energy stakeholders seeking sustainable and efficient energy solutions for cities.

The remaining parts of this research paper are structured as described below. Previous research is analyzed and discussed in Section 2. In Section 3, the suggested method is assessed, and its implications are examined. In the next part (section 4), the findings are reviewed, and a brief explanation is also provided for greater comprehension. The study ends in Section 5, which includes some thoughts on potential future work and the conclusion of the work.

2. Review of Literature

This section provides studies of several authors which were studied and researched on energy efficiency by utilizing IoT technologies.

Alzaroog and Emhamed (2024) [30] delved into the use of IoT technology to improve energy efficiency in metropolitan areas. The study integrated a comprehensive literature evaluation with an examination of several case studies. Smart buildings, energy grids, and transportation networks in cities are some of the main areas of concentration when it comes to the IoTs. Based on the results, it was clear that IoTs technologies can make cities more sustainable by cutting down on energy use.

Priyanka et al. (2023) [31] employed cluster-head election and region-based clustering model to enhance the energy efficiency of IoT networks in an agricultural environment (REAN). The region clustering and cluster head selection (RCHS) algorithm and the Shortest Routing and Less Cost algorithm (SRLC) were used in the suggested approach to provide software and IoT applications that were efficient in terms of energy consumption. Findings demonstrated that to validate the functionality of sustainable applications built on the IoT in a live setting.

Sikder et al. (2023) [32] delved into the crucial function of IT in promoting eco-friendly practices to improve energy efficiency and decrease carbon footprints inside corporate structures. The suggested research used a survey-based research approach to look at how different types of firms think about and behave when it came to using IT to help the environment. The findings highlighted the need to incorporate sustainable practices more extensively and engaged the sector to successfully tackle environmental challenges.

Martínez et al. (2022) [33] developed a "measure-analyze-decide and act" approach to calculating the Smart Readiness Indicator (SRI) for academic buildings to use as a benchmark for COVID-19 prevention and energy efficiency models. Findings shown that energy efficiency, performance audits, ultra-low consumption, and cost savings might be achieved by evolving to a smart campus as an experimental lab test. That test served as a proof-of-concept for IoT and SDG-enabling technologies towards Nearly Zero Energy Building (NZEB).

Riedelsheimer et al. (2021) [34] provided a framework for creating Digital Twins (DTs) of physical IoT items, the so-called DT V-Model, with the goal of improving the system's sustainability, especially in terms of environmental factors. It was improved with more roles and DT development techniques, building upon the V-model for the creation of smart goods. According to the results, the technique was well-suited for the multidisciplinary creation of DTs in Scenario B with an emphasis on sustainability, and the deficiencies in previous methodologies were filled.

Petrović and Đorđe (2020) [35] suggested a data-driven smart grid architecture that would make smart cities more energy efficient by concentrating on two areas follows energy trading and the charging of autonomous vehicles. Deep learning, linear optimization, semantic technology, simulation, domain-specific modeling notation, and relay protection components were all used by the framework. The findings indicated that the reduced cost of energy distribution was case-specific in case of energy trading the average cost reduction was 91 and in case of vehicle charging the average cos reduction was 59 for 8 consumers.

Parra et al. (2019) [36] designed a system that can integrate data from many sources. It was important to think about how much traffic each gadget made when data was integrated from many sources by the proposed system. Researchers suggested that each antenna used data aggruption to lessen the volume of 5G network traffic and then the energy usage. 150 individuals' electronic health records and three different health sensors were used to test the system. According to the findings, data aggruption might reduce traffic by as much as 70%.

Zhang et al. (2019) [37] investigated an IoT network containing wireless sensors and base stations that stated that power transfer techniques for supplying battery charging were becoming increasingly developed. A restart artificial bee colony (RABC) method was proposed to solve the subproblems of the data transfer model. It was proved that the RABC method asymptotically converged to the optimal solution of the problem. Numerical simulations showed that energy consumption in the studied network scenario can be minimized using the proposed method with a good, robust property.

3. Research Methodology

This research study involves implementing smart energy solutions in urban areas with high energy consumption, assessing and integrating existing infrastructure with renewable sources like solar panels and wind turbines, and backup generators. An IoT network comprising sensors, meters, and actuators monitor and manage energy flow. The installation includes assessing rooftops for solar panels, selecting sites for wind turbines, and strategically placing backup generators. The IoT control system features a data collection hub and user interface for remote management. Testing ensures component functionality and system integration, with continuous optimization and monitoring to enhance efficiency, anticipate maintenance needs, and prepare for upgrades.

3.1. Techniques Used

In this section, a description of the methods which are used in the proposed methodology is provided in detail.

- **RES: Solar and Wind System**

RES stands for Renewable Energy Source. This term encompasses the integrated use of renewable energy sources such as solar and wind power within a comprehensive energy infrastructure [38]. The RES described in the methodology involves the deployment of solar panels and wind turbines to generate electricity, along with the implementation of backup power sources and an IoT control system for monitoring and management. The RES outlined in the methodology is designed to leverage renewable energy sources like solar and wind to reduce reliance on non-renewable fossil fuels, decrease carbon emissions, and enhance overall energy sustainability. By integrating these renewable energy systems with modern infrastructure and control mechanisms, cities can achieve more efficient and resilient energy management while contributing to environmental conservation and mitigating the impacts of climate change.

Solar Energy System: Solar Energy system harnesses sunlight to generate electricity using solar panels. In the provided methodology, the steps for solar panel installation involve rooftop assessment to determine the best locations for maximum sun exposure and secure mounting. This includes ensuring structural integrity and proper orientation of the panels. Solar energy is a key component of integrated smart energy solutions, particularly in urban areas where rooftops can be utilized to generate clean electricity.

Wind Energy System: Wind turbines are utilized to convert wind energy into electricity. In the methodology, wind turbine installation involves careful site selection to maximize wind exposure and minimize visual and noise impact on the community. Wind energy complements solar energy, providing an additional renewable energy source for the integrated smart energy system. It's particularly advantageous in areas with consistent wind patterns, such as higher altitudes or open spaces.

- **Maximum Power Point Tracking (MPPT) Controller**

MPPT stands for Maximum Power Point Tracking which is a technique used in solar power systems to maximize the efficiency of solar panels by continuously adjusting the operating point where the panels produce the maximum power output [39]. Solar panels have a unique operating point called the maximum power point (MPP), which varies depending on factors like sunlight intensity, temperature, and shading. MPPT circuits dynamically adjust the electrical operating point of the solar panels to ensure that the circuits operate at or near their MPP, thus extracting the maximum available power from the sunlight. MPPT controller is shown in figure 2.

Fig 2. MPPT Controller [40]

In the designed model, MPPT controllers are essential in solar power systems to optimize energy harvesting, improve system efficiency, and maximize the return on investment by ensuring that the solar panels operate at their peak performance levels. During the installation of solar panels, MPPT controllers are employed to ensure that the panels operate at their maximum power output under varying environmental conditions such as changes in sunlight intensity or panel temperature.

- **Relay Circuit**

A relay circuit is an electrical circuit that utilizes relays to control the flow of electricity in response to certain conditions or signals. Relays are electromechanical switches that can be remotely operated, either manually or automatically, to open or close electrical contacts [41]. In the context of renewable energy systems (RES), a relay circuit can be used for fault control and mitigation.

A relay circuit in a RES function to detect faults or disturbances, such as equipment malfunctions or grid issues, through sensors monitoring voltage, current, temperature, or frequency. When a fault is detected, the relay circuit swiftly responds by rerouting electricity flow, isolating the faulty component, and minimizing downtime. Integrated into the RES control system, it works with sensors, actuators, and control units to ensure system reliability." Overall, the relay circuit plays a crucial role in enhancing the resilience and reliability of renewable energy systems by providing efficient fault control and mitigation capabilities.

- **IoT Control System using Server.**

The IoT control system using a server act as the backbone of the integrated smart energy solution, facilitating the monitoring, management, and optimization of energy flow within the system [42]. The IoT control system using a server plays a crucial role in ensuring the reliability, efficiency, and sustainability of the integrated smart energy solution by orchestrating the operation of renewable energy sources, backup power systems, and grid infrastructure in a coordinated manner [43]. The IoT control system utilizing a server serves as the central nervous system, orchestrating the entire operation from data collection to decision-making and control.

Sensors deployed across the grid gather real-time data on energy production, consumption, and system status, which is transmitted to the central server through the IoT network. At the server, the data is aggregated, processed, and analyzed using algorithms to identify patterns, predict demand, detect faults, and optimize energy distribution. Through a user interface accessible to city managers and technicians, the server provides real-time monitoring, alerts about critical events, and remote management capabilities. It controls actuators to adjust energy flow, reroute power during faults, and activate backup systems, ensuring uninterrupted energy supply and system reliability. Additionally, historical data stored on the server enables long-term analysis for performance evaluation and informed decision-making regarding system upgrades or expansions. Thus, the IoT control system acts as the backbone of the smart energy solution, ensuring its efficiency, sustainability, and resilience.

3.2. Proposed Methodology

In this section, the block diagram of the proposed methodology is shown in figure 3 and the steps are also given in detail below.

Step 1: System Design and Architecture Setup

● Identify Urban Areas for Implementation: Select areas within the city that would benefit most from integrated smart energy solutions, such as business districts or residential areas with high energy consumption.

● Infrastructure Assessment: Evaluate the existing electrical grid and infrastructure to determine the feasibility of integrating solar panels, wind turbines, and backup generators with power backup.

● Fault control and mitigation using relay circuit in RES: Implement a relay circuit within the renewable energy system (RES) to enhance fault control and mitigation capabilities. Design the relay circuit to swiftly reroute energy flow in the event of equipment malfunctions or grid disturbances, minimizing downtime and ensuring system reliability.

● Design IoT Network: Create a network architecture that includes sensors, meters, actuators, and control units to monitor and manage energy flow.

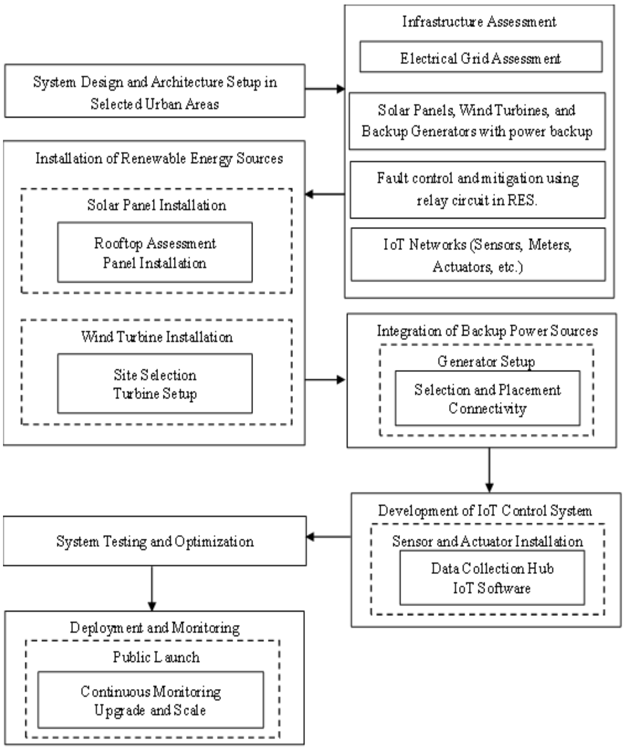

Fig 3. Proposed Architecture

Step 2: Installation of Renewable Energy Sources

- Solar **Panel Installation:**
  - ➢ Rooftop Assessment: Inspect rooftops for structural integrity and orientation to maximize sun exposure.
  - ➢ Panel Installation: Install solar panels on selected rooftops, ensuring optimal angle and secure mounting.
- **Wind Turbine Installation:**
  - ➢ Site Selection: Choose locations with consistent wind patterns, usually at higher altitudes or open spaces.
  - ➢ Turbine Setup: Erect wind turbines, taking care to minimize visual and noise impact on the community.

Step 3: Integration of Backup Power Source

- **Generator Setup:**
  - ➢ Selection and Placement: Choose a suitable type of generator (diesel, gas, etc.) based on availability and environmental guidelines; install it at a strategically beneficial location.
  - ➢ Connectivity: Integrate the generator into the overall grid to act as a backup during renewable source downtime or peak demand periods.

Step 4: Development of IoT Control System

- **Sensor and Actuator Installation:**

Deploy sensors across the grid to monitor energy production, consumption, weather conditions, and system status. Install actuators to control switches and breakers.

Data Collection Hub: Establish a central hub that collects data from all sensors and sends it to a central server.

- **Implementation of IoT Software:**
  - ➢ Programming: Develop or configure software to analyse incoming data, make decisions on energy distribution, and handle fault detection.
  - ➢ User Interface: Create an interface for city managers and technicians to monitor system performance, get alerts, and manage settings remotely.

Step 5: Testing and Optimization

- **System Testing:**
  - ➢ Functional Tests: Check all components (solar panels, wind turbines, sensors, actuators) for proper operation.
  - ➢ Integration Tests: Ensure the components work together as intended, the IoT network communicates effectively, and the backup systems activate correctly under various scenarios.
- **Optimization:**

Use data collected to fine-tune energy production, storage, and consumption, minimizing losses, and maximizing efficiency.

Step 6: Deployment and Monitoring

- **Public Launch**

Officially launch the system, beginning with a pilot area if necessary to gather initial public feedback and make further adjustments.

- **Continuous Monitoring:**
  - Performance Monitoring: Continuously analyse system performance to detect anomalies, predict future issues, and plan maintenance.
  - Upgrade and Scale: Based on performance data and city growth, plan to scale the system or upgrade components to handle increased load or improved technology

4. Results and Discussion

In this section, results and their discussion are presented in detail. The proposed "IoT enabled Integrated system for Green Energy into Smart Cities" is also presented which is implemented on the MATLAB.

4.1. IoT enabled Integrated system for Green Energy into Smart Cities using MATLAB.

The model describes the components and their functions according to the devised method using RES and backup units with ability to deal with faults and overload conditions using IoT enabled Integrated system composed of server and connected devices as shown in figure 4. It consists of a solar photovoltaic device with MPPT controller and integrated with voltage source control (VSC) based inverter controller which connects to the smart grid.

The SPV module generated AC voltage in volt and current in ampere is first amplified to higher voltages with less harmonic deviation using boost converter. The boost converter works as a power conversion unit by converting the AC voltage to DC supply for intended use. Battery module is connected to store DC power from the SPV module for later use. The amplified power is transmitted to the inverter which converts DC Voltages into AC voltages for long distance power transmission. It is connected to auxiliary backup supply unit in case of faults and overload by using fault generation block to test the durability of SPV system. It is connected to a relay circuit which used as fault control unit by tripping the SPV block from the rest of the components to prevent damage to main grid. It is also connected to bus for 3-phase power control and filtering unit to minimize losses and improving the efficiency of system.

The wind module supplies continuous source of power to the grid by stepping up the voltages using a transformer and it also connected to the bus for 3-phase power control and relay unit with fault control. It is also composed of backup auxiliary supply unit with energy storage in case of faults. It serves as an efficient tool for power supply in case of fault and damages. It is connected to the main grid by combining the power from other RES units in a synchronized manner to regulate the voltage supply based on the load distribution and power demand from the smart cities.

Diesel generator module is also added to serve as a continuous supply of power in case of no renewable energy is available in abundance or the load demand from the smart cities increases too much. It is connected to the transformer to step of the voltage supply to the grid with a backup auxiliary supply unit to work in case of faults. It is also connected to the relay circuit and fault generation block to account for power breakage and overloading conditions.

An IoT enabled server is designed which is shown in figure 4, with sensors and actuators connected across the overall system. It overlooks the performance and working of each RES unit, diesel generator unit and the main grid connected to the load across the smart cities and serves as data collection hub for IoT devices. It is connected to the mobile based application for Continuous Monitoring of the system. The user can check for the fault conditions and overload for electrical grid assessment.

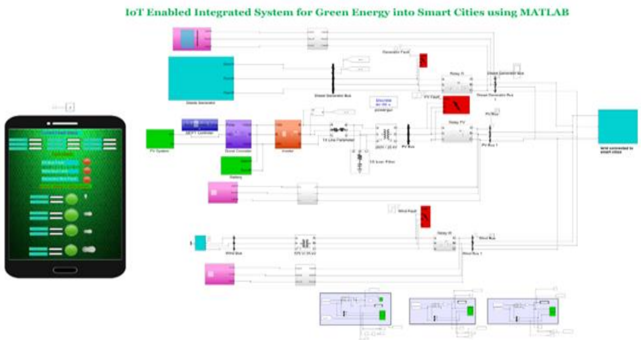

Fig 4. IoT enabled Integrated system for Green Energy into Smart Cities

4.2. Solar Photovoltic Device

In a solar photovoltic system, a voltage-source converter (VSC) with inverter unit is used to convert the DC output of the solar panels into AC power that can be fed into the grid. The VSC controller regulates the voltage and current output of the VSC to ensure that it matches the voltage and frequency of the grid. This process is called grid synchronization.

A solar PV system typically consists of a solar array, a VSC, and an inverter. The solar array converts sunlight into DC voltage. The VSC connected to the inverter unit converts the DC electricity from the SPV into AC voltage that matches the voltage and frequency of the grid. VSC controller ensures that the solar PV system operates safely and efficiently. The VSC controller regulates the voltage and current output of the VSC to meet the following requirements:

- The voltage output of the VSC must match the voltage of the grid.
- The frequency of the voltage output of the VSC must

match the frequency of the grid.

- The current output of the VSC must be limited to a safe level.

The VSC controller also protects the solar PV system from faults, such as overvoltage, under voltage, overcurrent, and undercurrent.

4.2.1. Voltage and Current

Figure 5 shows the voltage and current output from the solar photovoltaic device depicting the variation in AC voltage supply from the SPV module with time. Initially, it shows sudden drop in voltage and discrepancies with noise and harmonics due to insufficient power available across the system and load fluctuations. As the voltage and current supply from multiple units originates, the stability of SPV voltage and current profile is enhanced with reduced harmonic. It also supplies voltage to the battery unit for DC charging and industrial working purposes.

The voltage and current supply stabilize further as more and more supply is available to the smart grid from various RES and generator unit producing uniform power output in -50 to 50 kW range for generating constant DC voltage to the inverter module for conversion to AC voltage.

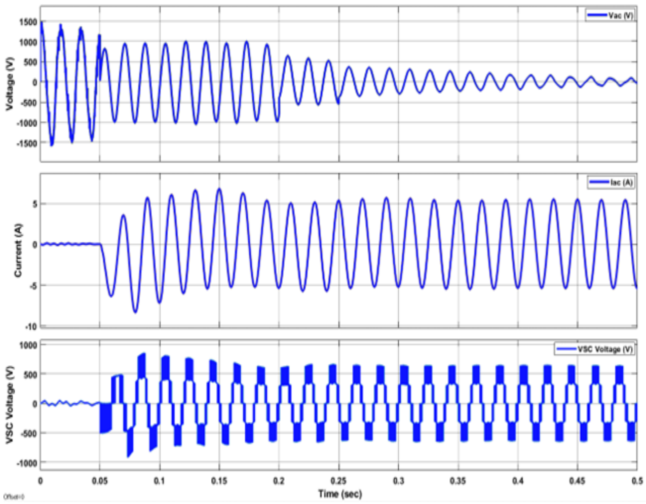

Fig 5. Voltage and Current for Solar Photovoltic Device

4.2.2. Power and DC output voltage from the inverter

Figure 6 shows the power output from the SPV module and DC voltage available depicting change in magnitude initially which stabilizes at 620 V with time.

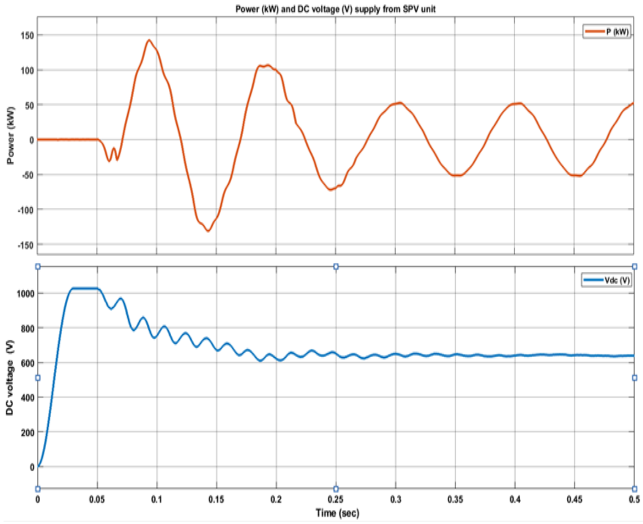

Fig 6. Power output from the SPV module and DC voltage

4.3. Wind Turbine

Wind turbine shows variation in the voltage and current values at the start as the wind turbine needs to reach a certain wind speed initially to start generating electricity. As the turbine blades begin to rotate and reach a certain speed, the voltage generation stabilizes. When turbine blades are not spinning at a constant speed it can cause variations in the output. The power electronics systems within the turbine converts the mechanical energy from the blades into electrical energy which also go through a calibration process during startup. In figure 7, y-axis shows the values for each parameter, while x-axis shows the time in seconds. All three parameters current, voltage, and power fluctuate at the beginning (around 0.1 seconds) and then stabilize at 0.25, 0.35, and 0.43 seconds, respectively.

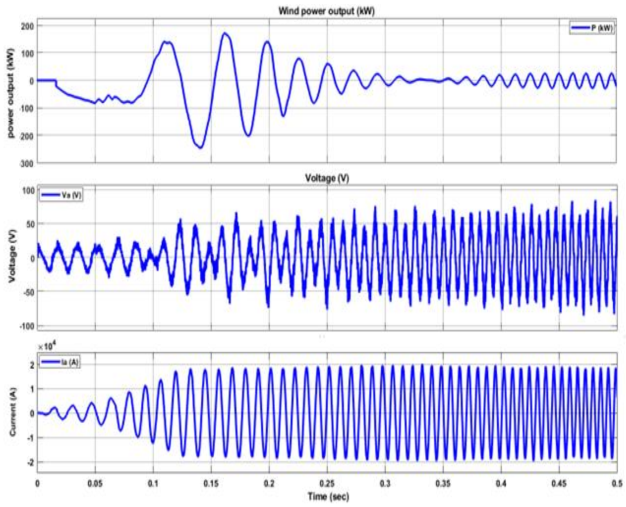

Fig 7. Wind Turbine

4.4. DG: Power output Voltage and Current

Diesel generator (DG) shows variation in the voltage and current values at the start as the DG needs to reach a certain RPM (revolutions per minute) initially to start generating electricity in figure 8. As the generator starts up, it may not be running at a constant speed it can cause variations in the output. The alternator converts the mechanical energy from the generator into electrical energy may also be going through a process of voltage regulation during startup. The DG set starts up at around 0 seconds. The voltage fluctuates the most during startup, reaching a peak of around 1500 volts and a valley of around -1500 volts. The current fluctuates between around 4000 amps and -4000 amps. The power output fluctuates between around 3000 kW and 0 kW. By around 0.2 seconds, all three parameters have stabilized.

Figure 8 shows how the current (A), voltage (V), and power output (kW) of a diesel generator (DG) set fluctuate during startup and then stabilize. The y-axis shows the values for each parameter, while the x-axis shows the time in seconds. All three parameters, the current, voltage, and power output of a diesel generator (DG) set fluctuate at the beginning (around 0.1 seconds) and then stabilize around 0.4, 0.45, and 0.35 seconds, respectively.

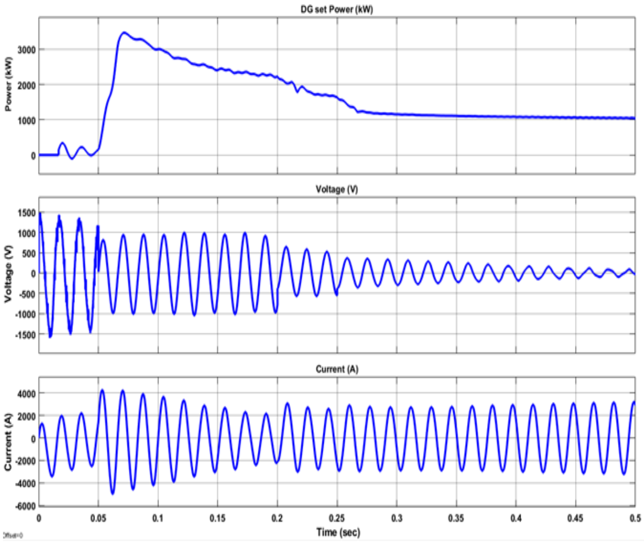

Fig 8. DG sets power output voltage and current

4.5. Battery: To Store the Excess Power Generated from RES

Battery is also integrated to store the excess power generated from RES in the form of DC power. It functions as the energy management device for the system. For sustainable energy conservation process, it is mandatory to include the components capable of storing large amounts of energy with high efficiency for later use. Figure 9 shows the voltage (V) and current (A) measurement of battery unit on y-axis over a time-period for simulation in seconds shown on x-axis. The voltage of the battery varies between the range of 258.565 V to 258.545 V showing optimal state of the battery controller for extended use to subsidiary circuits while the current starts at around 0.4955 A and increases to 0.4995 A over time.

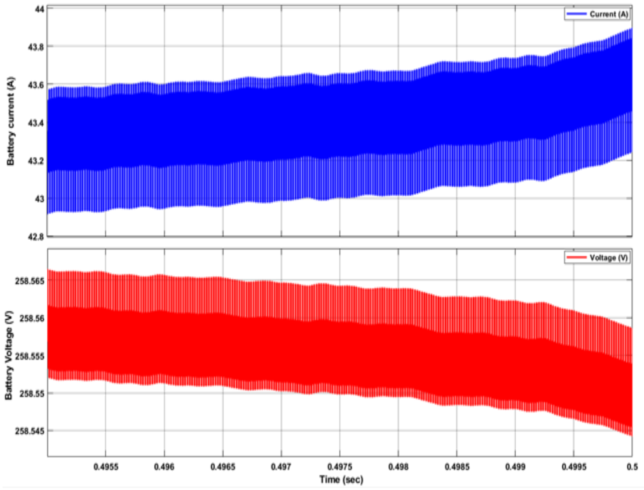

Fig 9. Battery

4.6. IoT Devices

Figure 10 shows the IoT application device displaying the state of smart grid and information regarding the power generation with faults and measurement levels about the solar PV, wind turbine, and diesel generator sources. Current power status shows the output from the solar PV, wind turbine, and diesel generator for all the three parameters i.e. Power (kW), Voltage (V), and current (A) respectively. The fault status for each power source shows the fault condition occurring during the normal operation of system forming the smart grid. In case of any fault or overload, the relay circuit trips the failure unit from the main line and instead of using the primary power source, it uses the backup power generation devices placed to deal with power shortage conditions.

The application also supports the functionality to evaluate the status of the branches in the grid system connected to the solar power bus, wind bus, and diesel generator buses providing valuable insights about the voltage and current flowing across the smart grid. It is helpful to ascertain the load distribution taking place within the grid system.

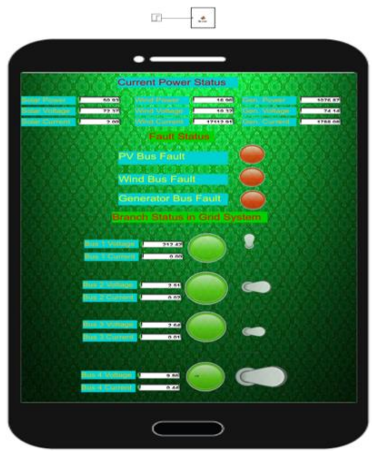

Fig 10. IoT Device

Consequently, the IoT device interface provides real-time monitoring of power generation, fault status, and grid branch status, facilitating load distribution assessment. This study offers a comprehensive approach to sustainable energy management in urban environments, leveraging IoT technology for efficient grid control and fault handling.

5. Conclusıon and Future Work

The research introduces an IoT-enabled integrated system for green energy deployment in smart cities, aiming to address the challenge of efficient integration of renewable energy sources. The proposed method introduces fault control and mitigation via a relay circuit in the RES, improving system reliability during grid disturbances. Installation of renewable sources, like solar panels and wind turbines, emphasizes site selection for optimal energy production. Integration of backup power, such as diesel generators, ensures continuous supply during downtime or peak demand. An IoT control system, with sensors and actuators, enables real-time monitoring and optimization. Testing and optimization phases ensure seamless integration for deploying a robust and scalable smart energy solution. Numerical results showcase the performance of various components: the solar photovoltaic (SPV) device demonstrates stabilized voltage and current output, with a DC voltage of 620 V from the inverter module. Wind turbine output stabilizes after initial fluctuations, while diesel generator sets stabilize around 0.35 seconds, exhibiting fluctuations in voltage, current, and power output during startup. The battery unit maintains a stable voltage range of 258.545 V to 258.565 V and increases in current from 0.4955 A to 0.4995 A over time. The IoT device interface provides real-time monitoring of power generation, fault status, and grid branch status, aiding in load distribution assessment. Furthermore, research efforts could focus on optimizing the communication protocols and data analytics algorithms within the IoT control system to enable more efficient energy management and decision-making processes.

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Author contributions

Yogita Patil[1]: Conceptualization, Methodology, Software, Field study**,** Data curation, Writing-Original draft preparation, Software, Validation., **Prachiti Suryavanshi[2]:** Visualization, Investigation, Writing-Reviewing and Editing.

Conflicts of interest

The authors declare no conflicts of interest.

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