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A brief overview of the physical layer test system: Development of an IoT-based energy storage and electrical energy distribution system

Muhammad Ikram Mohd Rashid[1], Dongdong Li[2], Jiang Xiaoxia[2]

[1]Faculty of Elektrical & Electronic Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Malaysia
[2]Department of Mechanical Engineering, Ningxia University, China

Corresponding author: mikram@umpsa.edu.my

Abstract
Solar power systems are an efficient and sustainable solution for household and commercial energy needs. This study discusses the integration of critical components such as solar panels, inverters, batteries, and charge controllers, as well as the use of IoT systems to monitor and control energy distribution. The results of the analysis show that using inverters to convert direct current (DC) to alternating current (AC) and store energy in batteries ensures the continuity of electricity supply. The IoT system also improves efficiency by providing intelligent control. In conclusion, this system offers high reliability and efficiency in utilising renewable energy.

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1. Introduction
In recent decades, global energy demand has continued to increase along with population growth and technological development. Dependence on fossil fuels, such as coal, oil, and natural gas, has led to significant environmental problems, including climate change and air pollution. In response to these challenges, renewable energy, such as solar power, has emerged as an environmentally friendly and sustainable solution. Solar energy through solar power technology offers great potential in reducing dependence on fossil fuels and their negative environmental impact (Jia et al. 2018; Shahsavari and Akbari 2018; Rahman et al. 2022). Solar power is one of the most reliable renewable energy sources, especially in areas that receive a lot of sunlight throughout the year (Khan and Arsalan 2016; Erdiwansyah et al. 2022b; Hossain et al. 2024). This technology converts solar radiation into electrical energy through solar panels or photovoltaic (PV) cells. In a solar power system, solar panels are the main component that produces electricity in direct current (DC) (Erdiwansyah et al. 2022a; Siow et al. 2024; Ying et al. 2024). The electricity produced can be used directly, stored, or converted to alternating current (AC) using an inverter for household electrical equipment needs.

Modern solar power systems rely on solar panels and inverters and involve several other essential components in increasing efficiency and reliability. One is the solar charge controller, which regulates the flow of electricity from the solar panels to the battery or load, ensuring that the battery is charged safely without the risk of overcharging or undercharging (Balog and Davoudi 2021; Dorel et al. 2023; Jawad et al. 2023). The battery is also an essential component in this system because it functions as a backup energy storage that allows electricity use when the solar panels are not producing energy, such as at night or when the weather is not supportive (Datta et al. 2021; Bai et al. 2024; Maka and Chaudhary 2024). In addition, the inverter's role in a solar power system is crucial. The inverter transforms direct current (DC) from solar panels or batteries into alternating current (AC), which is suitable for use by typical electrical appliances. Thus, the inverter ensures that the electricity generated by the solar panels can be distributed and used efficiently in homes or commercial facilities. The inverter technology used in these systems is also increasingly advanced, with some models providing the ability to manage energy distribution more intelligently through integration with modern control technology (Mahmoud et al. 2017; Xu et al. 2021; Souza Junior and Freitas 2022).
Using Internet of Things (IoT) systems in solar power management has introduced a new dimension in efficiency and monitoring. IoT allows remote monitoring and control of solar power systems, from battery charging status to energy consumption to power distribution (Bedi et al. 2018; Ramu et al. 2021; Sadeeq and Zeebaree 2021). With IoT technology, users can monitor system performance in real time and optimise energy usage based on the data obtained. Integrating IoT in solar power systems increases efficiency and ensures more innovative and economical energy use (Hossein Motlagh et al. 2020; Ahmad and Zhang 2021; Wu et al. 2022). Therefore, this article discusses integrating critical components in a solar power system, including the role of solar panels, inverters, batteries, solar charge controllers, and IoT technology (Richelli et al. 2021; Fagiolari et al. 2022; Nath et al. 2023). In addition, it will be explained how the protection system in the electric current ensures the system's operational safety and maintains the reliability of energy distribution. This study provides a comprehensive view of how solar power can be optimised for household and commercial electricity needs efficiently and sustainably, as well as the importance of utilising modern technology in improving the performance of this renewable energy system.
The purpose of this study is to deeply analyze the integration of critical components in a solar power system, including solar panels, inverters, batteries, charge controllers, and Internet of Things (IoT) technology, and evaluate how this combination can improve the efficiency, reliability, and sustainability of renewable energy use in the household and commercial sectors. The novelty of this study lies in the use of IoT technology in solar power systems to monitor and optimize energy distribution and storage in real-time, which has not been widely discussed in previous studies. Combining the IoT-based energy protection and control systems analysis, this study offers an innovative solution to manage solar energy more efficiently, safely, and integratedly.

2. Methodology

Fig. 1 shows an integrated solar power system that supplies electricity to a home, involving several essential components such as solar panels, an inverter, a battery, and the utility grid. The solar panels on the left side of the diagram capture the sun's energy and convert it to direct current (DC). Then, an inverter converts this DC energy into alternating current (AC), the kind of electric current that most household electrical appliances use. This system allows households to utilize renewable energy directly, minimizing dependence on electricity from the utility grid. In addition, the system is also connected to the public electricity network (grid) through a meter. The primary function of this meter is to measure electricity consumption from the grid. Still, in some scenarios, excess energy produced by solar panels can be channelled back to the grid. This process is called net metering, where households can "sell" unused electricity to the utility company, helping to reduce electricity bills and increase system efficiency. Integration with the grid also ensures that the home still has a source of electricity when solar energy production is insufficient, such as at night or during cloudy weather.

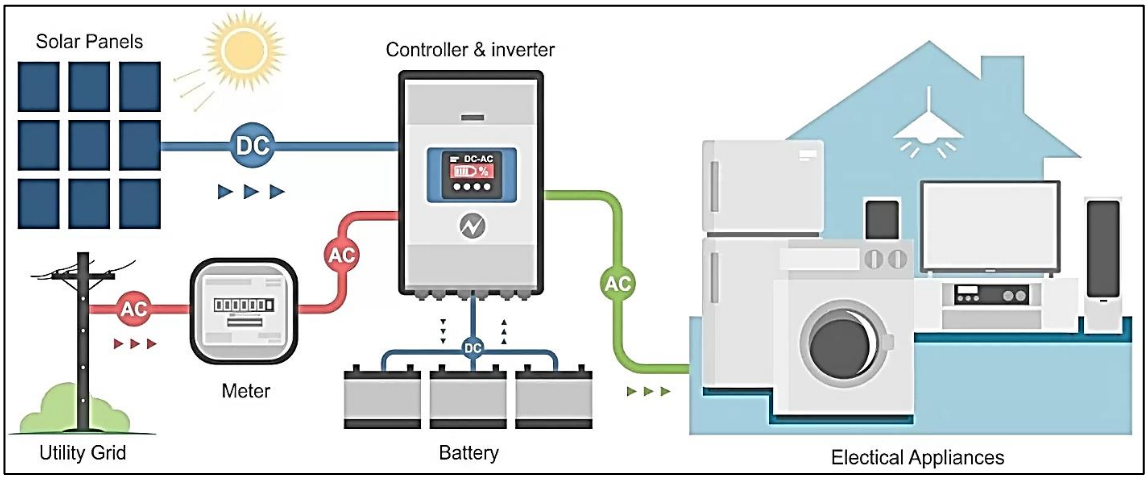

Fig. 1. Schematic diagram of the design of the Physical Layer Test System (PLTS) off-grid

The battery-powered energy storage system in the diagram centre is crucial for storing excess solar energy. Batteries store energy in direct current (DC), which can be used when the solar panels are not making enough electricity, such as at night or when household energy consumption increases. The inverter then converts the DC energy stored in the battery into alternating current (AC) so that electricity can continue to flow to the home and electrical equipment can continue to function without interruption. Finally, the inverter and control system regulates electricity distribution to electrical devices in the house. Energy from batteries, solar panels, or the grid is efficiently distributed to household devices such as refrigerators, washing machines, and televisions. This system allows households to optimise energy use from renewable sources and the grid while providing energy backup through batteries in the event of a power outage or a decrease in energy production from solar panels. This scheme provides an overview of the efficiency of an integrated renewable energy system, providing an energy-saving and environmentally friendly solution.

3. Result & Discussion

Fig. 2 shows the schematic of a solar-powered water pump system consisting of solar panels, a pump controller, and a submersible pump. This system is designed to utilize solar energy as a power source to operate a water pump that supplies water from underground to the surface. This system helps provide water in remote areas where conventional electricity networks do not exist. The solar panels at the top of the image serve as the primary energy source. When exposed to sunlight, they convert solar energy into direct current (DC) electricity. The electricity generated from these panels will be sent to the pump controller, which will regulate the flow of electricity to the water pump. Solar panels are ideal for this system because they work best in areas that receive a lot of sunlight, often areas with limited access to clean water.

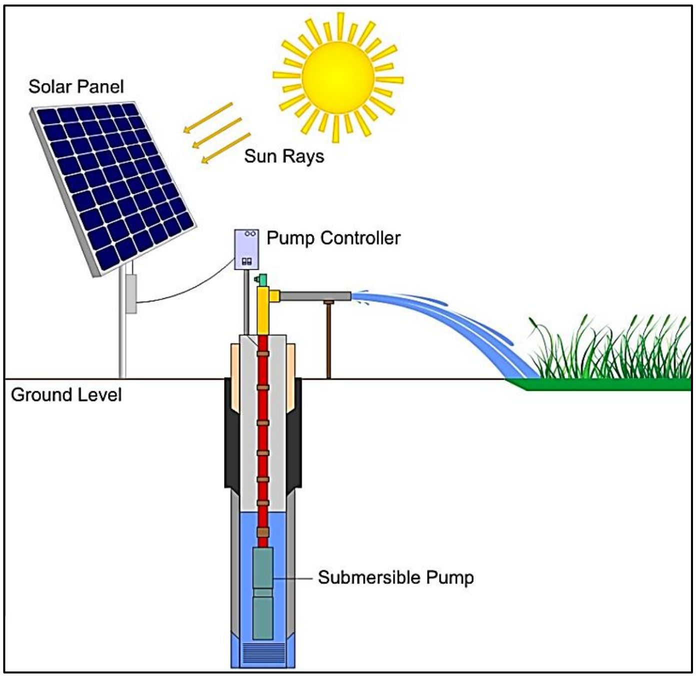

Fig. 2. Solar water pump

The pump controller plays a vital role in managing the energy received from the solar panels. It ensures the submersible pump gets enough power to operate efficiently without damaging the system components. In addition, the controller can also be equipped with an automatic feature that adjusts the pump operation based on the available water level or the water demand on the surface, thus preventing unnecessary energy usage. Submersible pumps are underground, pumping water from wells or underground water sources to the surface. Because these pumps are in the water, they are very efficient at lifting large amounts of water to the surface. These pumps are commonly used in agricultural areas for irrigation and places requiring a stable water supply. By using solar power, these systems are not only environmentally friendly but also reduce dependence on fossil fuels and conventional electricity, thus providing a sustainable solution for water resource management.

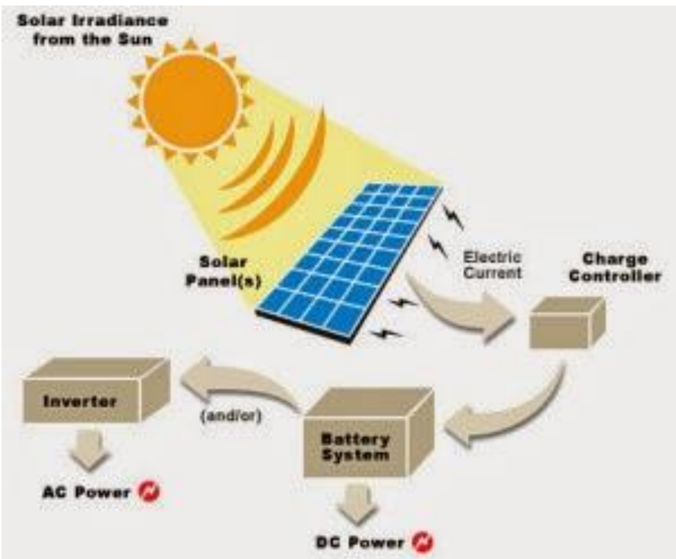

Fig. 3. Solar energy for electricity

Fig. 3 shows the basic schematic of a solar power system consisting of several main components, namely solar panels, charge controllers, battery systems, and inverters. This system utilises solar radiation converted into electrical energy and then distributed or stored for various electricity needs. Each component in this diagram has an essential function in ensuring the efficiency and stability of the energy supply from solar power. First, solar panels are the main component that converts solar radiation into direct current (DC). This process occurs through the photovoltaic effect in the solar cells that make up the panel. In this image, sunlight that falls on the surface of the solar panel produces an electric current, which is then sent to the charge controller. The more solar radiation the panel receives, the more electrical energy is produced.

Second, the charge controller plays an essential role in managing the flow of electricity from the solar panels to the battery system. This component prevents overcharging or excessive battery charging, which can damage the battery and reduce its lifespan. In addition, the charge controller also ensures that the electric current distributed to the battery remains stable and optimal, thereby increasing the system's efficiency. The charge controller regulates energy distribution from the battery to the inverter or electrical devices. Third, the battery system stores the solar panels' electrical energy. The energy stored in the battery is in the form of direct current (DC), and this system allows users to have a backup of electricity that can be used when sunlight is not available, for example, at night or when the weather is cloudy. This makes solar power systems more reliable because the electricity supply can continue without directly depending on sunlight. Finally, the inverter converts the direct current (DC) stored in the battery into alternating current (AC), which most household electrical appliances need. The inverter is a crucial component in this system because general electrical appliances cannot use electricity from solar panels or batteries without the conversion from DC to AC. This diagram illustrates how solar energy is converted, managed, stored, and distributed to meet sustainable and environmentally friendly electricity needs.

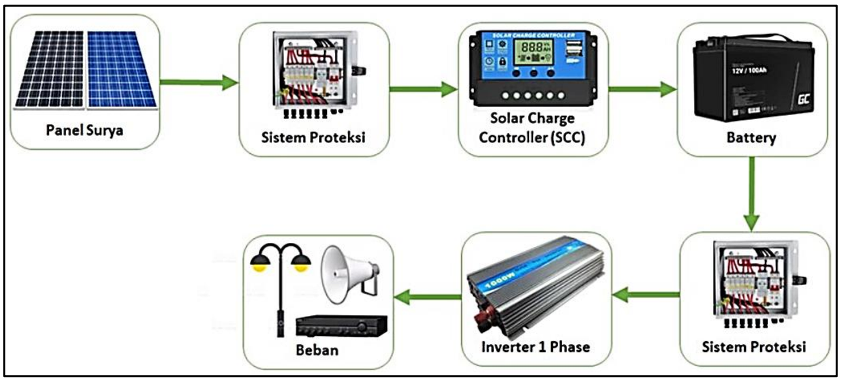

Fig. 4. Energy storage system in batteries

Fig. 4 shows a schematic of a solar power system consisting of several essential components: solar panels, protection systems, solar charge controllers (SCC), batteries, inverters, and loads. Each element has a specific function to convert, store, and distribute electrical energy from solar energy. This system ensures a stable and safe energy supply and minimises energy losses during distribution. First, the solar panels on the left side of the image function as the main component that converts solar energy into direct current (DC) electricity. The protection system then receives the solar panels' energy and shields the entire circuit from potential dangers like current surges or unstable voltages. By preventing unintentional current fluctuations from harming other components like batteries and inverters, this protection system is crucial to maintaining the system's dependability and safety.

Next, the Solar Charge Controller (SCC) controls the solar panels' electricity. The SCC manages battery charging by controlling the incoming current, preventing overcharging, and ensuring that the battery is not charged or drained too much. After going through the SCC, the electrical energy is stored in the battery shown in the picture. This battery stores energy in direct current (DC), which can be used when solar energy is unavailable at night or in cloudy weather. Finally, the energy stored in the battery can be distributed to the load through a 1-phase inverter. This inverter converts direct current (DC) from the battery to alternating current (AC), which most household electrical devices need. Before reaching the load, the electric current flows back through the protection system to ensure safety during energy distribution to loads such as lights or other electronic equipment. This diagram provides an overview of how a solar power system can convert, store, and distribute energy efficiently while considering safety and stability.

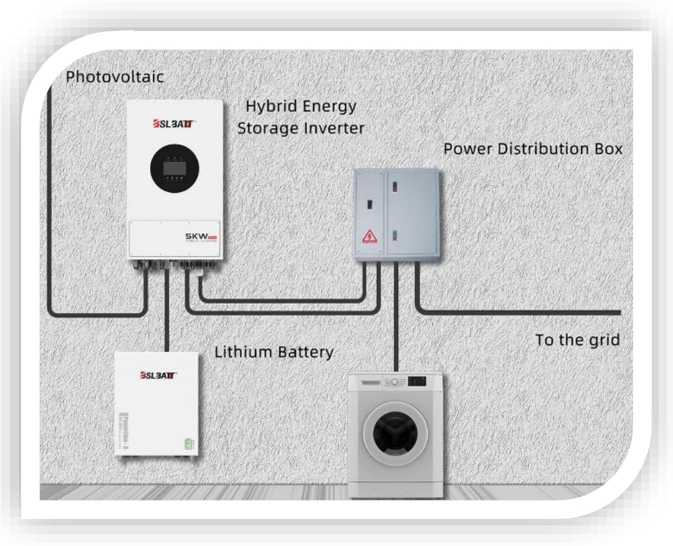

Fig. 5. Battery energy conversion by inverter

Fig. 5 shows a diagram of a solar power system consisting of several main components, namely photovoltaic (PV) panels, hybrid energy storage inverters, lithium batteries, power distribution boxes, and power grids. This system converts solar energy into electricity and stores it in batteries for later use by electrical equipment in the home or to be channelled back to the power grid. These components ensure a stable, efficient, and reliable power supply. First, photovoltaic (PV) panels function to convert sunlight into direct current (DC) electricity. The hybrid energy storage inverter transforms the direct current (DC) electricity these PV panels produce into alternating current (AC), which household electrical appliances can use. This inverter also manages the distribution of energy between direct use, storage in batteries, or energy flow back to the grid, depending on the energy needs at that time.

Another critical component in this image is the lithium battery, which serves to store the energy produced by solar panels. This battery stores energy in direct current (DC) and provides backup power when the electricity production from the solar panels is insufficient, for example, at night or during cloudy weather. Lithium batteries are known for their large storage capacity and long life, making them an efficient choice in renewable energy systems. The power distribution box in this system is responsible for distributing energy to the electrical equipment in the home. The connections to appliances like the washing machine demonstrate how the distribution box distributes the electricity from the inverter to meet the household's needs. The distribution box also serves as a safety device, regulating the flow of electricity throughout the home to prevent overloading and damage to electronic equipment. Finally, this system connects to the public electricity network (grid), which allows the household to flow excess energy back to the grid or draw electricity from the grid when the energy from the solar panels and batteries is insufficient. This provides flexibility in energy management so the household can maximise renewable electricity while having backup power from the grid when needed. Overall, this diagram illustrates how solar energy can be efficiently processed, stored, and distributed to meet household energy needs sustainably.

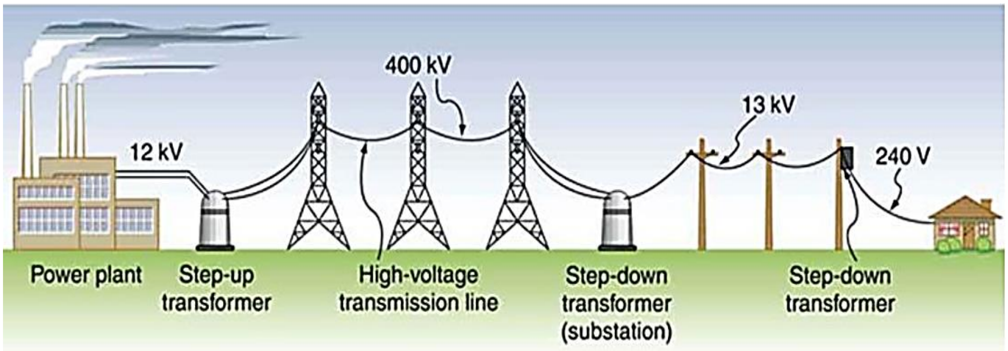

Fig. 6. The process of distributing electrical energy to homes

Fig. 6 shows a schematic of the flow of electrical energy distribution from the power plant to household consumers. This process involves several stages, from increasing the voltage at the power plant and long-distance transmission through high-voltage lines to reducing the voltage in homes. Each stage is vital to ensuring electricity can be distributed safely and efficiently. First, electricity is generated at the power plant with a voltage of around 12 kV (kilovolts). This voltage is relatively low and not efficient enough to be sent over long distances because it can cause significant energy losses.

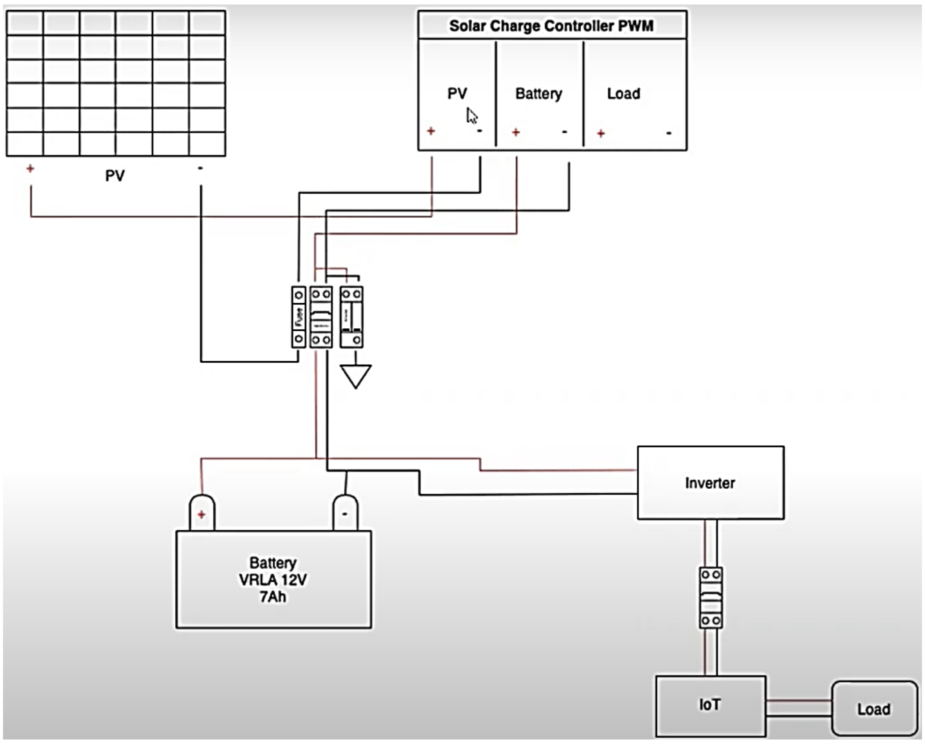

Fig. 7. IoT protection system and monitoring system

Therefore, a step-up transformer raises the voltage to a much higher voltage—roughly 400 kV—before sending electricity to the transmission network. This increase in voltage reduces energy losses during the transmission process. After the voltage is increased, electricity is sent through high-voltage transmission lines. These transmission lines are designed to carry electricity over long distances at very high voltages, making them more efficient in transporting electricity to various regions. A voltage of 400 kV allows the delivery of large amounts of energy with minimal power losses. This network usually includes tall transmission towers to maintain a safe distance between the power lines and the ground.

Step-down transformers at substations must again decrease the voltage when electricity reaches areas closer to consumers. At this stage, the voltage is reduced from 400 kV to around 13 kV for local distribution. However, this voltage is still too high for direct use by household appliances. Therefore, along the distribution line, a second step-down transformer is needed to decrease the voltage to 240 V, the voltage commonly used in households for everyday use. With this system, electricity can be distributed from the power plant to homes efficiently and safely. The voltage transformation process at various stages is essential to reduce energy losses during transmission and ensure that the voltage reaching homes meets safe standards for use by electrical appliances.

Fig. 7 shows a diagram of a solar power system involving several essential components such as solar panels (PV), a charge controller (solar charge controller PWM), a battery, an inverter, and an IoT (Internet of Things) system. This diagram illustrates how energy from solar panels is regulated, stored, and then distributed to meet the electrical load, with additional IoT features for remote monitoring and control. First, solar panels (PV) generate electricity through direct current (DC) from the solar energy received. The solar charge controller receives the electricity that the solar panels generate. In this diagram, the charge controller uses the PWM (pulse width modulation) method to regulate the voltage and current received from the solar panels to suit the battery's and load's needs. The charge controller prevents overcharging of the battery and avoids damage to the battery.

Second, the charge controller's energy is divided into two paths: one to the battery for storage and the other to the load that electrical devices can use directly. In this diagram, the battery used is a 12V VRLA battery with a capacity of 7Ah, which functions as backup energy storage. The energy stored in the battery is used when the solar panel does not produce enough power, such as at night or when the weather is cloudy. Third, the inverter converts the DC electricity stored in the battery or generated directly by the solar panel into alternating current (AC) electricity that household electrical appliances can use. This inverter is essential because most household electrical devices work with AC, not DC. In addition, this diagram also shows the presence of an IoT system connected to the inverter and load. The IoT system allows remote monitoring and control of the solar power system's performance, including information about energy usage, battery charge status, and load settings. Finally, this entire system shows how solar power components can work together to provide efficient and reliable energy, with the addition of sophisticated control from the IoT system. The charge controller's good protection and regulation system and IoT integration ensure that energy is used optimally and the battery remains safe, increasing the efficiency and durability of the entire solar power system.

4. Conclusion

The conclusion from the results and discussions above is that the solar power system shown in various diagrams can optimize the use of solar energy for household and commercial purposes by integrating several essential components, including solar panels, inverters, batteries, and charge controllers. Each element ensures efficient energy conversion, safe storage, and appropriate energy distribution for direct use or stored in batteries as a backup. This system also shows flexibility in energy management with an inverter that converts direct (DC) electricity to alternating (AC), allowing household electrical devices to operate correctly. Adding an IoT system in several schemes strengthens control and monitoring, allowing users to manage energy consumption and system performance more intelligently and efficiently, thereby increasing the reliability and effectiveness of the overall system in addition, using batteries as backup energy storage allows the system to continue operating even when there is no direct supply from the solar panels, such as at night or during bad weather conditions. This adds to the reliability and continuity of energy supply for users. The protection system shown also plays a vital role in maintaining safe operations, avoiding overcharging the battery, and protecting components from damage due to voltage surges. Overall, this solar power system is an efficient and environmentally friendly solution to meet the energy needs of households and small industries, with the addition of IoT-based monitoring features that maximise the efficiency, safety, and sustainability of using renewable energy from the sun.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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