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Integration of Solar Energy into Smart Grids: A Cost-Effective Framework for Sustainable Power Management

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Abstract: Providing reliable electrical power to consumers at minimal cost presents a significant hurdle, particularly given the rising energy expenses owing to limited transmission capacity and the additional strain on power plants required to ensure a consistent supply. Renewable energy sources, particularly solar power are crucial for the future evolution of power systems owing to their cost-effectiveness and eco-friendliness. These alternatives offer new ways to complement existing grid infrastructure. Over the past ten years, various factors have reduced barriers to entry for photovoltaic systems, including improved solar cell efficiency, decreased costs, increased government incentives, and other considerations. Consequently, photovoltaic (PV) systems have become increasingly prominent in the global energy landscape. This project aims to develop a model for an intelligent power system that integrates multiple grid-synchronized energy sources. This system reduces consumer unit costs, ensures a steady electricity supply, enhances the current grid by feeding back excess power, and employs a smart algorithm to select the optimal power source from among the various options. Furthermore, it provides a locally generated, relatively affordable, and efficient solution for both businesses and consumers.

Keywords: Photovoltaic systems, intelligent algorithms, charge controller, grid tie inverter, smart power system.

Introduction

The developed nations are experiencing a consistent rise in the demand for electricity production. It is impossible to recreate the capacity and opportunity need for energy that is continually expanding. This is due to a number of factors, the most important of which is the building of newly built transmission lines. Developing countries are particularly challenging when it comes to locating appropriate right-of-ways (Dokas et al., 2022). Energy is critical to the activities that we engage in on a daily basis. Coal, petroleum, and natural gas are the three types of fossil fuels that make up the world's supply. It is anticipated that these fossil fuels will be depleted in the near future. Despite the fact that the quantity of power is decreasing, and the cost of using is increasing, which is leading to shortage of energy and causing inflation. As a result of the significant increase in energy usage, the traditional technique of generating power via the burning of fossil fuels is no longer sufficient to supply the demand. Apart from that, utilizing fossil fuels leads to environmental difficulties. CO_2, methane, also other harmful gases may play their part in pollution and global warming. The key objectives of this study are:

- To layout a complete model that incorporates numerous grid-synchronized energy sources, leveraging sophisticated algorithms to optimize power source selection based on cost, availability, and dependability.
- To emphasize the vital role of solar energy and other renewable sources in the future development of power systems, stressing breakthroughs in solar technology and the falling costs of photovoltaic systems.
- To stimulate the use of pollution-free, renewable energy sources, highlighting the potential of smart power systems to support and develop sustainable energy infrastructure.

This study includes the linking of numerous power stations to the electricity grid. The system involves:

- PV Panel as Resource
- Utility Grid
- Grid Tie Inverter
- Control System

Energy is collected from the PV panels and delivered into the residence area. Excess electricity is provided into the utility grid by making use of grid connection inverters. This method is applicable to any or all the places which are domestic power producing and making the grid system more efficient and dependable. This approach should operate base of Micro grids. In accordance with Micro Grid Institute, “micro grid is a tiny energy system with the capacity of managing captive supply and need sources to keep up steady solution within a defined boundary (Sondawale et al., 2018). A Micro Grid is a hybrid system comprised of numerous different types of electrical energy sources, including green energy sources: photovoltaic, wind turbines, small hydro, and fuel turbines using biogas (Mushtaq et al., 2016), but also generators that run on conventional fossil fuels (on a smaller scale), and various types of energy storage (battery packs, gas cells, flywheels, and water pump). Local energy assets, sources, and technologies are integrated and exploited inside the Micro Grid in order to satisfy the demands of the end users, which may vary from basic electrification to more advanced or complicated services (Pandiyan et al., 2024). First and foremost a grid tie inverter is employed by utilizing the support of filters, and detectors synchronize the effectiveness of the grid because of the PV producing panel. This strategy may not only balance the provide and demand requires of grid however will likely minimize the system price of client as nearly all the power demanded in smart house will soon be dependent on its PV that is own panel. Then it will harvest the residual power from the other source for example the grid if it part is unable to supply the electricity to load (Deshmukh & Chandrakar, 2022; Singh et al., 2023).

Materials and Methods

Renewable Energy Sources

Green energy sources are usually considered the source of energy which is generated from sectors that are regenerated on a daily basis, such as sunshine, wind, rain, tides, waves, and geothermal heat. Green energy is displacing daily used traditional fuels in four different sectors: electricity production, hot water/space heating and rural energy solutions. Green energy comes in a variety of ways (Mulenga et al., 2020). These kinds of energy are all based on sunshine in some way. Wind and hydroelectric power are direct consequences of differential heating at the Earth's surface, which results in the movement of air (wind) and the formation of precipitation after the atmosphere is elevated. Solar energy is a direct conversion method that does not need panels or collectors (Rai et al., 2023). Biomass sources of energy are concentrated sunlight contained inside flowers (Zaidi et al., 2023). Other renewable energy sources that are not dependent on sunlight include geothermal energy, that is a result of nuclear reactions into the bedrock at the initial temperature of the Earth's formation, and tidal energy, which is a transformation of gravitational energy (Festus et al., 2023).

Solar Energy

This kind of energy is dependent on the fusion that occurs at the Sun's core. This energy is gathered and converted in a variety of distinct ways. The spectrum extends from simple solar power fluid heaters with solar power enthusiasts to sophisticated solar power direct conversion technologies such as electrical reflectors and boilers or photovoltaic panels for residential usage (Rai et al., 2023; Rai et al., 2024).

MPPT Charge Controller

Within the MPPT controller, a DC to DC converter is included. This converter allows the solar panel to operate at its rated capacity and step down the current to recharge the battery pack at its voltage level by raising the billing current, thus boosting the solar panel's energy output. The foundation of MPPT, Solar Charge Controller is electrical monitoring, and includes nothing in associating along traveling the plates by having a tracking device, this is definitely solar. Alternatively, the operator explains the solar panel production and how it compares to the battery pack current. Following that, it estimates the amount of energy that the panel can generate to charge the battery. MPPT simply takes this power and transforms it to the optimal voltage for maximum charging current in the battery pack (Ur Rehman et al., 2021).

DC to DC Boost Converter

An electronic circuit or electromechanical device known as a DC-to-DC converter transforms a direct current (DC) source from one voltage level to another. A boost converter is used to increase a source voltage to a higher level. The primary parameter, such as input and output voltage, inductance, capacitance, and resistor values, as well as the obligation terms of percentage, were calculated. The duty cycle (D) is used to influence the boost converter selection. When a boost converter is used in PV applications, the data related to voltage beginning from the PV panel changes according to natural circumstances (Sumathi et al., 2015).

Results and Disscussion

Lab Simulation

In Figure 1, it is noted that the generation of the sine wave is done by a three-stage process comprising various circuits responsible for converting direct current (DC) to alternating current (AC). The first circuit presumably conducts the initial DC to DC conversion, scaling up or down the voltage as needed. An inverter that transforms the modified DC voltage into a pulsed or quasi-sinusoidal waveform could be used in the second circuit. In order to simulate a pure sine wave, the third circuit is usually a filter, or a sequence of filters, that smooth down the waveform. This multi-phase conversion procedure guarantees that the output AC is excellent and appropriate for a range of uses.

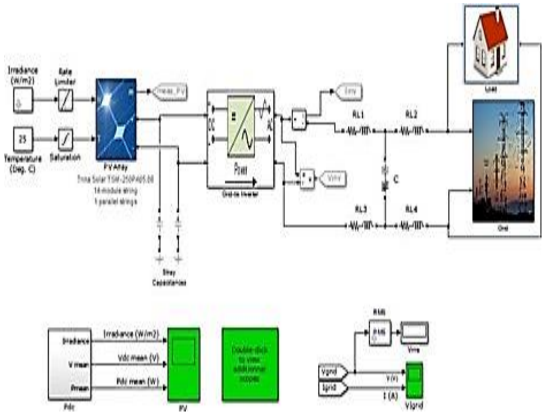

Fig. 1 Simulation of solar with inverter synchronization

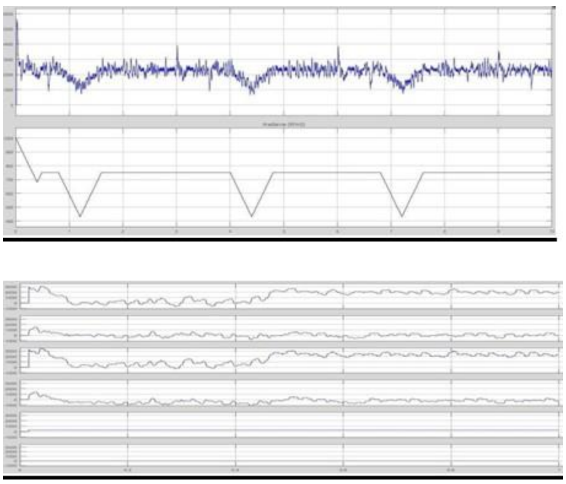

Fig. 2 Active and reactive power of grid, inverter & load.

In Figure 2, the active and reactive power characteristics of the grid, inverter, and load are presented, highlighting their interactions within the power system. Active power indicates the true power absorbed by the load, whereas reactive power depicts the power that oscillates between the source and load, vital for voltage regulation. To address the harmonics created during the DC to AC conversion, filtration techniques are applied to eliminate distortion and assure a smoother, more stable output waveform. The prototype of this study, which incorporates various components and filtering techniques, is given in Figure 2, exhibiting its practical use and efficacy in regulating power quality and system performance.

Figures 3(a) and (b) depict the prototype built for converting DC to AC power. The images disclose the main components of the system, including a battery, a Grid Tie inverter, a microcontroller (Arduino), a transformer, and a 50-watt load (bulb). This prototype illustrates a single set of the total circuit configuration. In this configuration, the Grid Tie inverter processes direct current (DC) electricity from the battery to produce alternating current (AC). Effective power conversion and regulation are made possible by the microcontroller (Arduino), which is essential to managing and regulating the system's performance. The transformer modifies the voltage levels to meet the load's needs. Three of these sets of circuits are used in parallel to provide a three-phase AC output, which is commonly used for industrial and high-power applications. Each set is in charge of transforming DC power into one phase of the three-phase AC supply, which when combined gives users a stable and balanced power source.

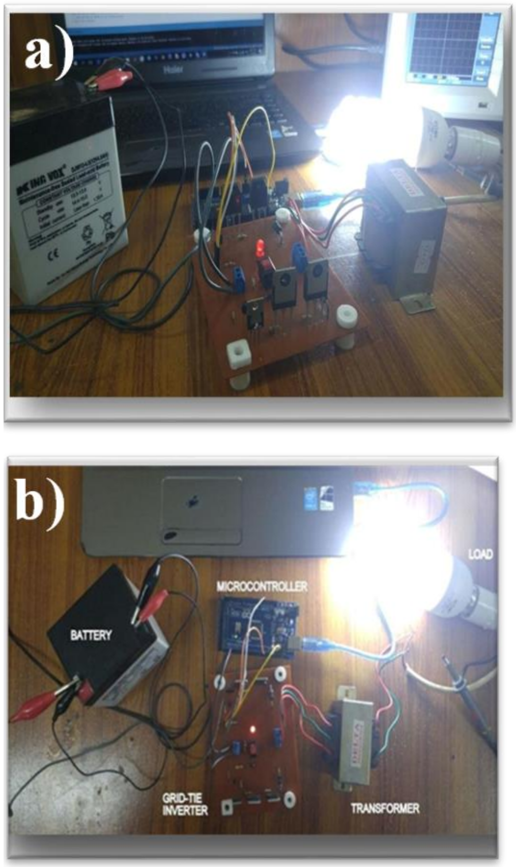

Fig. 3 a) Inverter powered by a battery and controlled by PWM signals b) Inverter powered by a battery and controlled by PWM signals.

Figure 4 illustrates the Grid Tie inverter is utilized in the project. This vital element is in charge of converting the solar panels' continually changing direct current (DC) electricity into a steady alternating current (AC) that may be sent into the electrical grid. The Grid Tie inverter carries out a number of essential tasks. Firstly, it stabilizes the solar panels' fluctuating DC output, which is subject to variations owing to variations in sunshine intensity and other reasons. After that, it transforms the stabilized DC power into AC power that is compatible with the grid's voltage and frequency. The inverter makes sure that solar electricity can effectively synchronize with the electrical system of the grid by accomplishing it. This procedure aids in preserving the general stability and dependability of the power supply in addition to making it possible to integrate renewable solar energy into the grid.

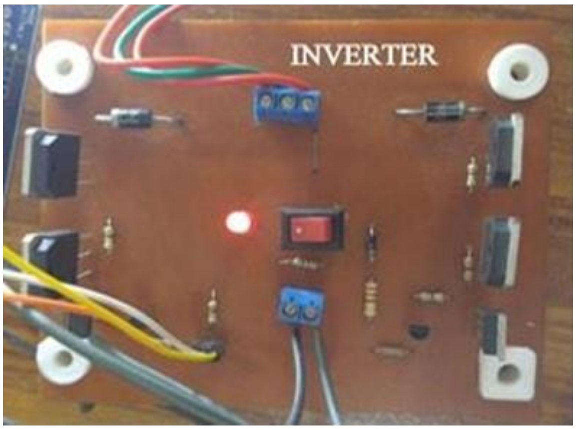

Fig. 1 Grid tie inverter.

Figure 5 displays the zero crossing detector, which employs a basic operational amplifier (op-amp) circuit. The major function of this detector is to determine the moment at which an AC signal crosses the zero voltage level, which is vital for many applications such as phase-locked loops, power measurement, and waveform synchronization. In this circuit, the op-amp compares two input voltages: One is the AC signal whose zero crossings are to be detected, and the other is a reference voltage, normally set at zero volts. When the AC signal crosses the reference voltage, the op-amp's output changes state, generating a digital signal that shows the zero crossing point. This output can then be utilized to synchronize other components or systems, ensuring exact timing and control in the entire circuit functioning.

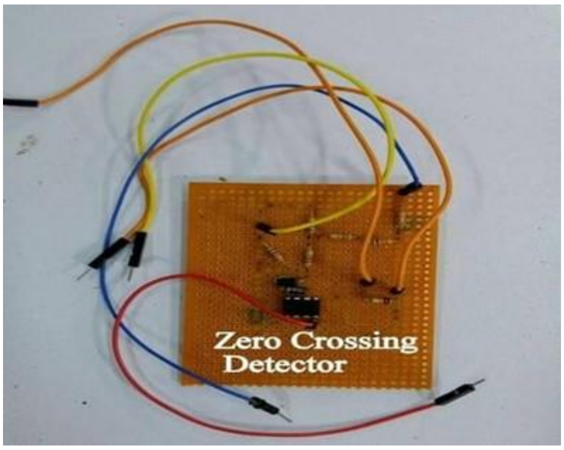

Fig. 2 Zero crossing detector.

Figure 6 shows a DC boost converter, a type of switch-mode power supply, especially designed to increase the input voltage of an uncontrolled DC supply to a stable higher output voltage. The boost converter functions by storing energy in an inductor during the 'on' phase when a switch (usually a transistor) is closed, and then releasing that stored energy to the output through a diode when the switch is open during the 'off' phase. This method essentially ramps up the input voltage to a greater level. The converter features feedback systems to manage the output voltage, ensuring it stays stable despite fluctuations in the input voltage or load circumstances. This makes the DC boost converter a crucial component in situations where a greater voltage is required from a lower voltage source, such as in battery-powered gadgets, renewable energy systems, and electric cars.

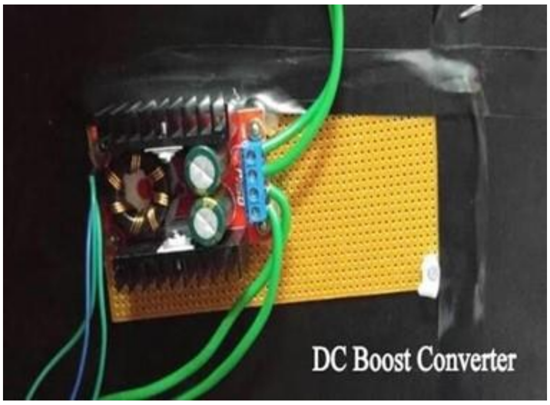

Fig. 3 DC boost converter.

Cost Effective Source

The intelligent algorithms employed in integrating solar energy into smart networks prioritize picking the most cost-effective power source by combining predictive modeling, dynamic decision-making, and optimization strategies. For example, Long Short-Term Memory (LSTM) models are applied to estimate solar energy generation, allowing the system to anticipate and plan around the changeable availability of renewable energy. Reinforcement Learning (RL) frameworks, including Deep Deterministic Policy Gradient (DDPG), play a crucial role in real-time decision-making by continuously altering battery charge and discharge processes to optimize profit and efficiency based on current energy demands and available resources. Additionally, Energy Management Systems (EMS) balance supply and demand, factoring in both predicted insights and real-time grid data to increase reliability. Optimization techniques, such as Particle Swarm Optimization (PSO) and Genetic techniques (GA), establish the ideal blend of renewable and non-renewable energy sources, as well as storage options, to reduce costs. By integrating these advanced methodologies, alongside AI, IoT, and blockchain technologies for increased transparency and stability, the algorithm ensures that the most cost-effective power source is selected dynamically, ensuring efficiency and sustainability within the smart grid.

Conclusion

The successful monitoring of the solar panel output, including accurate voltage, current, and power data, facilitated a smooth transition between the solar panels and the continuous power supply. This transition offers significant economic benefits in terms of electricity production, income generation, and capital investments. Furthermore, utilities and the entire power infrastructure could benefit from the influx of low-cost or free solar energy into the grid to encourage the increased adoption of renewable energy nationwide. This system can optimize power acquisition costs from various sources, particularly during the summer when electricity prices typically peak on the hottest and sunniest days of the year.

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