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Original Research Paper

Modeling and Implementation of a Hybrid Solar-Wind Renewable Energy System for Constant Power Supply

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Abstract: In recent years, Uganda has significantly increased the use of renewable energy sources, particularly solar and wind power. These energy sources are especially crucial in rural and remote areas where connecting to the national grid is challenging. Renewable Energy Sources (RES) have proven to be cost-effective alternatives to traditional energy sources, which often require substantial investments in transmission and distribution networks. This study focuses on designing and implementing a hybrid renewable energy system that integrates both solar and wind power. The research successfully established a reliable and continuous power supply for the community through the combination of wind and solar energy. The hybrid power generation system operates by simultaneously monitoring solar and wind energy using an ACS712 current and voltage sensor. Controlled by a microcontroller, the system employs dual-channel relay switches to activate the power source with sufficient energy to charge the battery. The programming for this system was conducted using C++ and Arduino software. This study highlights the vast potential within the field of sustainable energy. With rapid and economical electricity production, this hybrid system paves the way toward a greener future, where our energy needs can be met in an environmentally friendly manner.

Keywords: Renewable Energy, Solar Energy, Wind Energy.

1. Introduction

Due to the depletion and rising costs of non-renewable resources, there has been a significant rise in the demand for renewable energy. The combined effects of urbanization and population growth have escalated energy consumption and demand. This rapid and substantial increase in energy needs has led to energy shortages and higher costs. Consequently, researchers and scientists are increasingly focusing on alternative, cost-effective, and eco-friendly energy sources. To supplement the inadequate supply from conventional energy sources, renewable energy options like solar, wind, tidal, geothermal, and biogas should be utilized [1] [2] [3] [4]. In the 21st century, solar, biogas, and wind energy are the most commonly used renewable sources due to their abundant availability, flexibility, user-friendliness, affordability, and non-toxicity. Solar and wind energy have garnered considerable attention because they are natural resources that are easy to implement [5] [9].

The fundamental component of a solar energy system is the Photovoltaic (PV) module, which is made up of solar cells. These cells convert sunlight into electricity through the photovoltaic effect, which occurs in specific semiconductor materials like silicon, germanium, and selenium. PV systems are evaluated based on their peak power, which is the maximum power output they can achieve under Standard Test Conditions (STC). The efficiency of power generation from solar modules is influenced by various factors including temperature, light intensity, and the spectral qualities of sunlight [7] [8]. Under STC, the conditions are defined as a temperature of 25°C, solar irradiance of 1000 W/m², an air mass of 1.5, a wind speed of 2 m/s, and the solar panels oriented to face south [2] [3]. The optimal power generation by photovoltaic systems occurs when sunlight strikes the panel perpendicularly. Enhancing the power output from PV systems can be achieved by integrating PV Efficiency Enhancement (EE) systems such as solar tracking mechanisms and Maximum Power Point (MPP) tracking systems [1] [10] [11] [17].

Wind is generated by the uneven heating of the Earth by the sun, resulting in air movement across the planet's surface due to pressure differences. This kinetic movement of air produces significant renewable energy [6] [18]. Devices that harness wind power to generate electricity are known as wind turbines. A wind turbine converts the kinetic energy of wind into rotational mechanical energy, which is then transformed into electricity using a generator. The blades of typical wind turbines rotate at speeds ranging from 13 to 20 revolutions per minute, depending on their technology, and can operate at either a constant or variable speed. The rotor's speed is adjusted relative to the wind speed to optimize energy conversion efficiency [19] [20] [12]. The wind turbines come in two main types: fixed-speed and variable-speed turbines. Fixed-speed turbines achieve maximum efficiency at a specific speed. In these turbines, the rotor speed remains constant regardless of wind speed, determined by factors such as the gear ratio, the supply grid frequency, and the generator design.

2. Literature Review

In [13] [21] [22], the researcher evaluated various optimization strategies for scheduling energy in hybrid power generation systems. The scheduling considered factors such as the fuel expenses of thermal power plants and their emissions. Various optimization methods were applied, including genetic algorithms, pattern search techniques, and interior point methods [14] [22]. Although this research was quite innovative, it faced issues with robustness and accuracy during conversion and switching processes. A power management strategy based on current control was proposed for distributed power generation systems. This strategy utilized a Reference Current Generator (RCG) to regulate the three-phase inverter and manage the power flow between distributed generation sources, the electric grid, and load demands under both balanced and unbalanced grid conditions [23] [24] [25]. While effective, the design relied heavily on non-renewable sources, which diminished its potential for a reliable, low-cost power supply. Another approach described in this paper involved the development of a dual power generation system combining solar panels and wind turbines, featuring two solar modules and horizontally rotating wind blades. The system also included an energy storage unit and a charge controller to enhance overall energy conversion efficiency [15] [26]. This design was well-developed but was not implemented for practical use and involved complex circuitry, resulting in high costs.

A method for autonomously controlling active power in a small-scale photovoltaic system was introduced to aid synchronous generators' inertial response and load-frequency control [16] [27]. The control strategy implemented a grid frequency regulation system that incorporated both slow and fast frequency response features. However, significant energy losses occurred during the transfer from renewable sources to the grid, making this approach less effective and durable. A hybrid power generation system combining solar and wind energy was designed [24] [28]. This system provided stable power through its dual-energy configuration, where solar panels converted solar energy to electricity and wind turbines converted wind energy to electricity [25] [28]. Developed in 2017, this system lacked several modern technologies, including solar energy optimization, which was not addressed in its design and development. Consequently, it proved inefficient, failing to generate enough energy to fully support conventional power sources.

This review clearly highlights that integrating solar and wind power can generate sufficient electricity to support communities in Uganda with limited access to reliable power. Specifically, the unstable electricity supply in Nyamarungi village, Bukanga, Isingiro district, Uganda, illustrates this issue. Uganda predominantly relies on hydroelectric power, which depends on flowing water. During dry seasons, the reduced water levels lower the flow rate, diminishing turbine speed and, consequently, power output. To address these limitations, this research focuses on developing and implementing a hybrid solar and wind power generation system to provide sustainable energy. The system will utilize cascaded silicon-based wafers and a horizontally rotating prototype wind turbine to generate electricity. The primary objective is to create a hybrid power generation solution that delivers clean, safe, and reliable power to Nyamarungi village, Bukanga, Isingiro district, Uganda.

3. Methodology

3.1. Working Principle of the Control Systems

Figures 1 and 2 illustrate the control unit's block diagram and the flowchart of the proposed hybrid system, respectively.

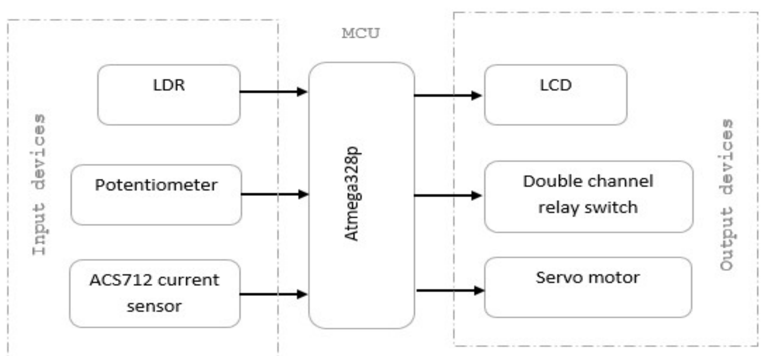

Figure 1. Block Diagram of the Control Unit of The System

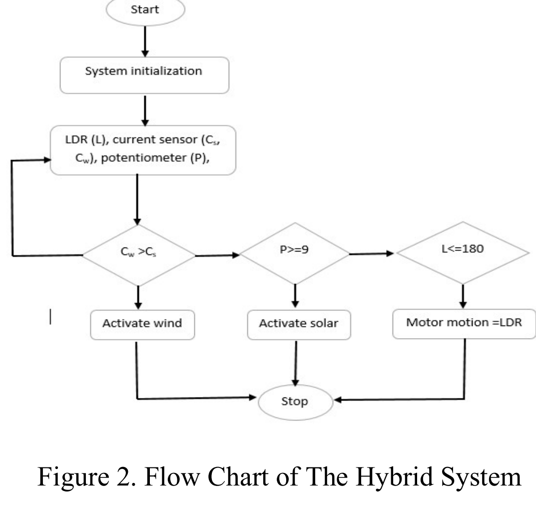

Figure 2. Flow Chart of The Hybrid System

The dual power generation system for solar and wind operates as follows: the ACS712 current sensor and a voltage sensor are employed to simultaneously monitor solar energy from the sun and wind energy from the wind turbine.

To ensure that the power supply is sufficient to charge the battery, double-channel relay switches are used. For demonstration purposes, a 10K potentiometer varies the voltage from the solar panel using the voltage division principle. All system activities are displayed on a liquid crystal display (JHD16X2A). Additionally, the system includes an automatic solar tracking mechanism that orients the solar panel towards the maximum solar exposure. This mechanism utilizes a light-dependent resistor to measure light intensity and optimize solar energy capture

3.2. Materials

Hardware Components Used for the Design are:

a) Control system: Atmega328p, Crystal oscillator, Ceramic capacitors, and IC socket.
b) Input devices: LDR, Potentiometer, and ACS712.
c) Output devices: I2C LCD 20x4, Servo motors, LEDs, and Double channel relay
d) Power supply unit: DC battery, Semiconductor diode, Filtering capacitor, Voltage regulator, L7805 and L783.3, Capacitors and resistors, Solar panel, Dynamo
e) Accessories: Vero board, Casing, Female to male jumpers, Terminal block, and Ribbon wires.

3.3. System Controller Unit

The system control unit features a microcontroller unit responsible for executing software to monitor input parameters, process data, store information, and control interfaced peripherals, such as DC motors.

a) Microcontroller (ATMEGA328P)

A microcontroller is a compact integrated circuit designed to manage specific tasks within an embedded system. Typically, it includes a processor, memory, and input/output (I/O) peripherals all on a single chip [29] [30] [31].

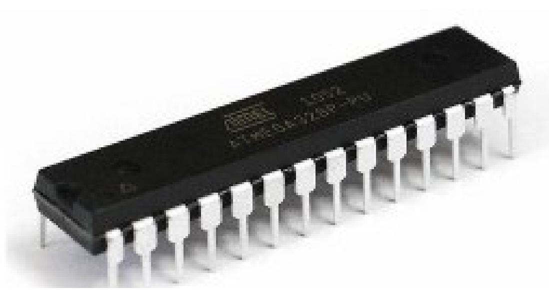

Figure 3. Microcontroller (ATMEGA328P)

The Atmel Atmega328p is an 8-bit microcontroller equipped with three ports (B, C, and D), which provide General Purpose I/O (GPI/O) pins. These pins can be configured as inputs or outputs to control various actuators, including DC motors. Figure 3 shows a typical Atmel Atmega328p microcontroller [32] [33] [34].

b) Crystal Oscillators

A crystal oscillator is an electronic circuit that uses the mechanical resonance of a piezoelectric crystal to generate a stable electrical signal at a fixed frequency. For this system, the crystal oscillator operates at 16 MHz and serves as the external clock source for the Atmega328p microcontroller. It works in conjunction with 22 pF ceramic capacitors, which help prevent debouncing in timers. Figure 4 illustrates the ceramic capacitors used in this setup [33] [35].

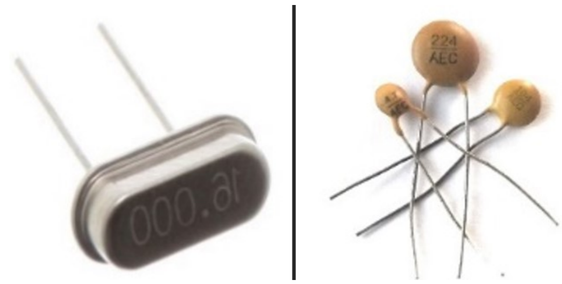

Figure 4. Capacitors

c) Pull-up Resistor
A resistor is a passive two-terminal electrical component that provides electrical resistance within a circuit. In electronic circuits, resistors are utilized to reduce current flow, adjust signal levels, divide voltages, bias active components, and terminate transmission lines, among other functions. For instance, a pull-up resistor is used to connect unused input pins (such as those on AND and NAND gates) to the DC supply voltage (VCC), ensuring that the input remains HIGH [36]. To prevent continuous resetting of the Atmega328p microcontroller, a pull-up resistor should be connected to its reset pin.

d) Light Dependent Resistor.
A Light Dependent Resistor (LDR), also known as a photoresistor, photoconductor, or photocell, is a device whose resistivity varies based on the level of incident light. These light-sensitive devices are constructed from semiconductor materials with high resistance, as illustrated in Figure 5**.** The principle behind an LDR is that its conductivity increases when exposed to light, leading to a decrease in its resistance.

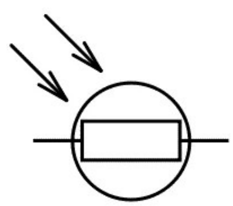

Figure 5. Light Dependent Resistor

e) Potentiometer
Potentiometers are adjustable resistors used in various applications, including audio equipment and as position transducers in devices like joysticks. They work by varying the resistance within a circuit based on the position of a movable wiper mechanism. Figure 6 shows a diagram of a potentiometer, illustrating its components and operation.

Figure 6. Potentiometer

f) ACS712 Current Sensor

A current sensor is a device designed to detect and convert electrical current into an easily measurable output voltage, which is proportional to the current flowing through a circuit. As current passes through a conductor, it generates both a voltage drop and a surrounding magnetic field, which are utilized in current sensor designs. There are two main types of current sensing: direct and indirect. Direct sensing, based on Ohm's Law, measures the voltage drop across passive electrical components to determine the current. Indirect sensing relies on Faraday's and Ampere's Laws to detect current via magnetic fields. Figure 7 illustrates a typical ACS712 current sensor.

Figure 7. ACS712 Current sensor

g) Liquid-Crystal Display

A Liquid-Crystal Display (LCD) is a flat-panel display that utilizes the light-modulating properties of liquid crystals combined with polarizers to create images. **Figure 8** shows an LCD module used to display the status of the entire proposed system [32] [38].

Figure 8. Liquid-Crystal Display

h) Relay switch

A relay switch operates on the principle of electromagnetic induction. When current flows through an electromagnet, it generates a magnetic field. The relay typically includes multiple contacts: Normally Open (NO), Normally Closed (NC), and Common (COM). These contacts enable the relay to connect or disconnect high-current loads.

Figure 9. Relay Switch

The relay can be activated by either AC or DC currents. In AC relays, the coil is demagnetized at each zero crossing of the current, which can lead to intermittent circuit disruption. Figure 9 depicts a typical relay switch.

i) Servo Motor
A servo motor is designed for precise rotation and control. It typically includes a control circuit that provides feedback on the motor shaft's current position, allowing the motor to achieve accurate movement. A servo motor comprises a motor (either DC or AC), a potentiometer, a gear assembly, and a control circuit. When powered by a DC supply, it is referred to as a DC servo motor, while an AC-powered version is called an AC servo motor. Figure 10 illustrates a typical servo motor device.

Figure 10. Servo Motor

4. Finding and Discussions

All components are assembled on a breadboard to test the concept of the research operation before moving to a Printed Circuit Board (PCB) for final implementation. The results were favorable, as each component performed its intended function, starting from the +5V power source derived from the laptop via the Arduino Uno power cable USB, and extending through the board to all other components. Figure 11 displays the soldered components on the PCB, demonstrating a robust and continuous circuit outline with all components connected serially from VCC and ground to the microcontroller connections.

Figure 11. Vero Board with Soldering

After soldering, a crucial continuity test was conducted to verify that connections were intact from one point to another and to ensure there were no short circuits between VCC and ground. The continuity test was successful with no errors detected, allowing the circuit to be powered. Consequently, all components performed as expected. Figures 12 and 13 display the results after soldering the PCB and powering the device.

Figure 13 shows the complete hybrid solar and wind turbine system. At its core, this advanced setup features the Atmega328P microcontroller, which intelligently manages battery charging and provides real-time voltage data on the LCD.

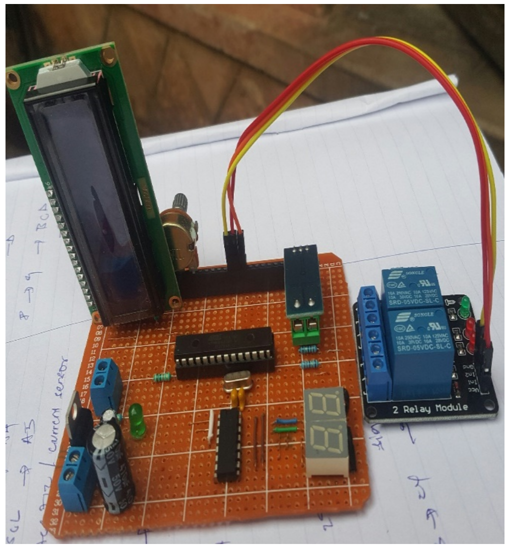

Figure 12. Control Circuit of Assembled Components

Figure 13 illustrates the hybridized solar-wind renewable energy system. The wind turbine, optimally positioned to capture wind energy, activates when sufficient wind is available, generating energy used to charge the battery and enhance the system's overall power supply. Concurrently, a solar panel mounted to maximize sunlight exposure captures solar energy, which is also directed towards charging the battery, further strengthening the system's power reserves

Figure 13. The Hybridized Solar and Wind Renewable Energy Prototype

When optimal natural conditions are present, the wind turbine and solar panel work together to charge the battery more rapidly. Their combined efforts enable a swift and cost-effective charging process, highlighting the significant benefits of utilizing multiple renewable sources simultaneously.

This research exemplifies the efficient use of natural resources, demonstrating that integrating wind and solar energy not only generates electricity but does so in a fast and economical manner. It stands as a model of innovation, guiding the way toward a greener, more sustainable future powered by natural forces

5. Conclusion

The hybridized solar and wind turbine system detailed in this research represents a significant advancement in renewable energy technology. By skillfully integrating wind and solar power through an advanced setup managed by the Atmega328P microcontroller, the system demonstrates exceptional efficiency and innovation. The coordinated operation of the wind turbine and solar panel, which charges the battery more quickly under favorable conditions, highlights the substantial benefits of combining multiple renewable sources. This research not only showcases the effective use of natural resources but also exemplifies the boundless possibilities in sustainable energy. With its rapid and cost-effective electricity production, the hybrid system paves the way toward a greener future, where energy needs are met in an environmentally friendly manner. It serves as a powerful example, encouraging the adoption of similar innovative solutions and advancing towards a more sustainable future powered by nature

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