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Developing and Controlling a PV-FC-BESS-Powered Hybrid Renewable Energy System in a LabVIEW Setting for Supporting Short- and Long-Duration Irrigation in Distant Rural Areas for Paddy Fields

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Abstract: In today's world, minimising reliance on carbon-based energy sources is crucial, especially in agricultural irrigation practices. Traditionally, diesel-powered pumps have been widely used for irrigation. However, these pumps are not only costly to operate but also contribute significantly to environmental pollution. Therefore, adopting alternative, eco-friendly technologies is imperative. A viable solution lies in the use of a Hybrid Renewable Energy System, which integrates a photovoltaic (PV) panel, a fuel cell (FC), and a (BESS). This hybrid setup is designed to supply 0.4 kW of single-phase electricity, making it suitable for operating irrigation pumps with capacities of up to 0.5 HP in various weather conditions. The performance of the HRES has been studied under different solar radiation levels and fluctuating load demands, utilising real-time data for both solar availability and power usage. The entire system is managed through a control setup implemented in the LabVIEW environment to ensure efficient energy distribution and system stability.

Keywords: BESS, FC, Hybrid Renewable Energy

1. Introduction:

The rate of energy consumption is strongly linked to the advancement of human society. In the current era, there is a growing demand for green energy sources. The adoption of green revolutions in agriculture has significantly enhanced grain production while also increasing energy consumption, primarily due to the improved use of agricultural technologies, especially in irrigation systems. Unlike many other sectors, agriculture is both energy-intensive and highly sensitive to energy availability, accounting for approximately 4–8% of total energy consumption.

Paddy cultivation is especially water-intensive. On average, producing 1 kilogram of raw rice requires around 2500 litres of water, sourced through either rainfall or irrigation. During the reproductive phase of the rice crop, it is essential to maintain a minimum water depth of 10 cm in the field for a period of 20 to 30 days to ensure healthy crop development. In addition to relying on rainfall, farmers utilise various irrigation methods to meet their water needs. One common approach involves extracting water from deep wells using diesel-powered pumps. However, these diesel pumps are costly and pose significant risks to both environmental and ecological systems.

A viable alternative is the use of hybrid renewable energy systems, which can deliver a consistent and reliable power supply suited to the required load for irrigation purposes. Several forms of renewable energy technologies have become well-established and advanced, including photovoltaic (PV) panels, wind energy systems, fuel cells, particularly hydrogen fuel cells (HFCs), natural gas-based generators, and battery energy storage systems. This paper proposed a centralised EMS for a standalone DC microgrid integrating solar PV, fuel cells, and BESS. The EMS aimed to enhance BESS lifespan, ensure system reliability, and minimise hydrogen usage. A PV de-rating strategy prevented battery overcharging during low loads, while a reverse sigmoidal function adjusted fuel cell output based on battery SoC. The EMS's performance was validated through simulations and hardware testing under various operational scenarios.[1]

The study focused on designing, simulating, and evaluating a renewable energy system to meet the annual energy demands of a 100 m² residential home in Turkey. The system comprised photovoltaic/thermal (PV/T) panels, batteries, a PEM electrolyser, hydrogen storage tanks, and PEM fuel cells. A zero-dimensional mathematical model was developed for each component. Results indicated that 20 PV/T panels (32.71 m², 62 kW), 8 batteries (192 kWh), and 7 hydrogen tanks (29.4 kg)

could fully supply the home's energy needs for one year. It was also observed that from December to April, the stored hydrogen met the home's electricity requirements.[2]This study introduced a novel method to assess the integration of solar PV and wind turbines with Electrolyser-Fuel Cell Systems (EFCS) and Battery Energy Storage Systems (BESS). A hybrid optimisation algorithm combining Particle Swarm Optimisation (PSO) and Genetic Algorithm (GA) was used to minimise the weighted average cost of energy (WA-CoE) while maintaining a desired renewable energy fraction (FRES). Among six evaluated scenarios, the PV-wind-BESS configuration achieved the lowest waCOE of 0.1838 €/kWh, demonstrating strong potential due to complementary resource availability.[3]This study focused on managing power in an autonomous hybrid system combining solar PV, hydrogen fuel cells, and lithium batteries. Using macroscopic energy representation and a maximum control structure, the system supplied remote regions in southern Algeria while minimising hydrogen consumption through effective energy management and DC/DC converter control.[4]This study investigated a hybrid power system integrating photovoltaic (PV) and fuel cell sources. Fuzzy logic and RBF neural network-based MPPT methods were developed, along with a switched inductor VMC for higher voltage gain. The system's performance was simulated in MATLAB/Simulink under varying conditions to assess dynamic behaviour.[5]This study proposed a grid-connected PV–fuel cell–electrolyzer hybrid system using a modified LMS algorithm for fixed power dispatch and power quality control. Variations in PV output were balanced by the fuel cell, while excess PV power produced hydrogen via an electrolyser. Simulation and hardware tests validated system performance.[6]This study presented the integration of a fuel cell system with an isolated photovoltaic (PV) system to create a standalone microgrid. Specifically, a 20 kW proton exchange membrane fuel cell (PEMFC) was combined with a 75 kW PV system. A dynamic model of the PEMFC stack was developed to analyse the system's behaviour. The performance of the proposed microgrid was evaluated under varying load conditions, and the response of the system to changes in fuel cell power output was thoroughly examined. The entire setup was thoroughly tested and validated using the OPAL-RT 4510 real-time simulator, and the resulting outputs were duly documented.[7]Reducing carbon-based energy use remains a major 21st-century challenge. This study presented a Hybrid Renewable Energy System (HRES) comprising a PV generator, a fuel cell, and battery storage. Designed for 0.5 HP irrigation pumps, it delivered 0.4 kW under varying conditions and was controlled using the LabVIEW environment.[8]This study addressed sustainable electric vehicle (EV) charging using a solar PV, fuel cell, and battery-based system. A high-gain, fast-charging DC/DC converter with a controller was implemented. Validated through MATLAB/Simulink, the system showed efficient performance, delivering higher charging currents and reducing overall charging time.[9]

This paper is organised as follows introduction in Section 1, Section 2 provides a modelling of HRES, Section 3 proposes an experimental Hybrid Power System, Section 4 provides a Matlab implementation and discussion, and Section 5 concludes the paper along with recommendations for future research.

2. PROBLEM STATEMENTS

A detailed field study was carried out in collaboration with local farmers in the southern region of Bihar, India, where paddy cultivation is a primary agricultural activity during the monsoon season. Certain areas within this region are hilly and remain disconnected from the national power grid. Based on insights gathered from the farmers, several important conclusions were drawn.

1. Rice cultivation typically requires about 10 mm of water daily.

2. During the reproductive stage of the rice crop, it is essential to maintain a minimum water level of 10 cm in the field for a duration of 20 to 30 days.

The total water demand for rice is generally estimated using basic water balance models, which account for various inflow and outflow components in the paddy field.

$$ER + I = ET + P + S + SD + CWS \quad (1)$$

Where ER refers to effective rainfall,

I denotes the irrigation input,

ET represents evapotranspiration losses,

P stands for deep percolation losses,

S indicates seepage losses,

SD refers to surface drainage or runoff losses,

and CWS signifies the change in water storage or status.

Based on Equation 1, it is evident that in the absence of sufficient rainfall, irrigation becomes the sole contributor to maintaining the water balance. A simple estimation shows that to sustain a 10 cm water level over a 1-hectare paddy field, approximately 1 million litres (1 mL) of water is needed. According to the performance and technical details provided in Table I, the selected water pump can meet this demand within 2 to 3 hours, making it suitable for timely irrigation in paddy fields.

Given this context, the primary objective is to develop a hybrid renewable energy system (RES) consisting of photovoltaic (PV) panels, a fuel cell (FC), and a battery energy storage system (BESS). This system aims to deliver a consistent power output of 0.4 kW throughout the day and night, in all weather conditions. The goal is to replace diesel-powered pumps to reduce operational costs and mitigate environmental harm. In addition to supporting irrigation, this hybrid system can also supply electricity for household lighting during non-irrigation periods, making it a cost-effective, efficient, and reliable solution.

In the next section, a brief description of this hybrid system's components and working is given.

3. Mathematical Modelling of System Components

The schematic of the HRES in standalone mode, as employed in this investigation, is shown in Fig.1. The different subsystems are described here.

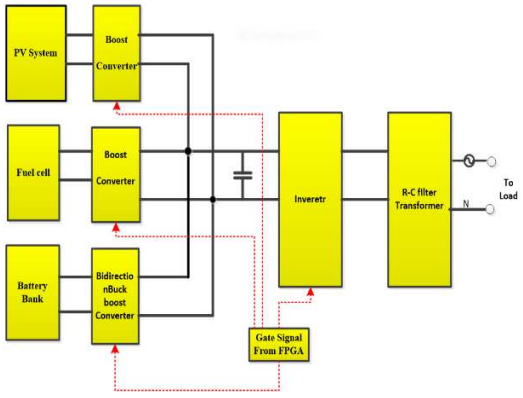


Fig.1. Configuration and Components of HRES

3.1 Solar PV Module

A PV module is made up of several solar cells that are arranged in series-parallel configurations to produce the appropriate amount of electricity. The equivalent circuits of the solar cell and the PV module are shown in Figures 2(a) and (b), respectively. Rsh and Rs represent the intrinsic shunt and series resistances of the solar cell, respectively, while Ns and Np represent the number of series and parallel connected solar cells, respectively, in the PV module.[10]

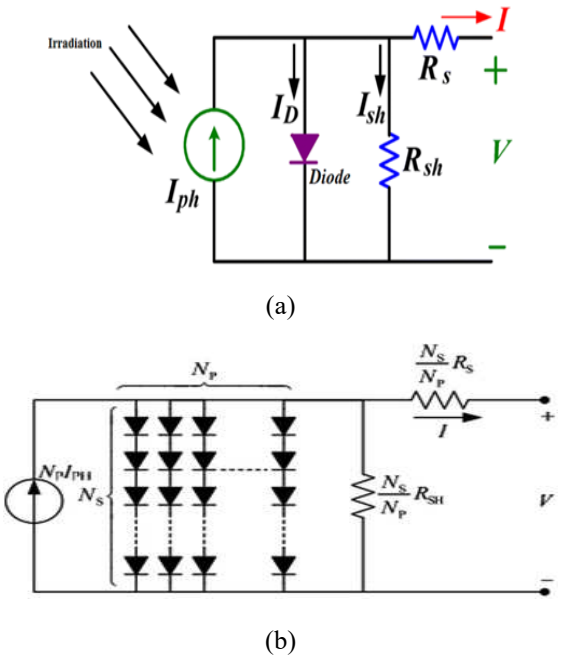


Fig.2. Equivalent circuits of (a) Solar cell, (b) PV module[10]

The following is a mathematical explanation of the PV module's current balance equation:

$$I = I_{ph} - I_d - I_{sh} \qquad (1)$$

where, in turn, I, Iph, Id, and Ish stand for output current, cell photocurrent, currents through the diode, and shunt resistance, respectively.

Shockley's diode equation is

$$I_d = I_0 \left[\exp\left[\frac{(V+IR_S)}{\eta V_t}\right] - 1\right] \qquad (2)$$

By Ohm's law

$$I_{sh} = V + I\frac{R_S}{R_{sh}} \qquad (3)$$

Substituting Ish and Id in equation (1), then.[11]

$$I = N_P I_{ph} - N_P I_0 \left[\exp\left[\frac{\frac{V}{N_S}+\frac{IR_S}{N_P}}{nV_t}\right] - 1\right] - \left(V\frac{N_p}{N_s} + I\frac{R_S}{R_{sh}}\right) \qquad (4)$$

Where

$$V_t = K\frac{T}{q} \quad (5)$$

Technical details of PV[12], [13], [14], [15]

Operating temperature	47°C
Efficiency	17%
Derating factor	80%
Temperature coefficient	-0.38%/Ω
Voc	47.5V
Isc	9.64A
Rated output power	1KW

*The pricing shown is based on information gathered from regional Indian manufacturers and wholesalers.

3.2 The Hydrogen Fuel Cell

An electrochemical device, such as an FC, transforms chemical energy into electrical energy in the same way as any battery. The FC is made up of many cells stacked together to form a single unit. In an FC power plant, chemical energy is transformed into electrical energy by reacting with hydrogen and oxygen[[16]

Nernst's instantaneous voltage output equation, which may be stated as follows, serves as the foundation for the mathematical modelling of the HFCs in the proposed system.[6]

$$E = N_O[\,E_O + \frac{RT}{2F}\,log\left[\rho H_2 \frac{\sqrt{\rho O_2}}{\rho H_2 O}\right]] \quad (6)$$

where NO denotes the stack's number of series FCs;

F is the Faraday constant [C/kmol];

R is the universal gas constant [J/kmol K];

PH2, partial pressure of hydrogen [atm],

PH2O, partial pressure of water [atm],

and pO2, partial pressure of oxygen [atm].

3.3 Battery Energy Storage System(BESS)

The BESS's ampere hour (CAh) and watt hour (CWh) capacities should be chosen such that, in the case of low solar irradiation and/or wind speed, they can sustain the load needed for longer[17]

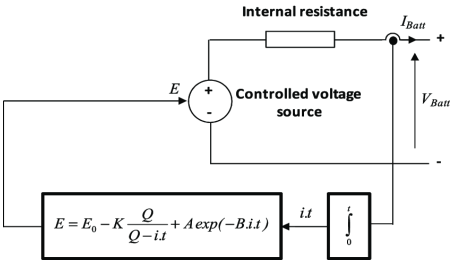


Fig.3. Generic Battery model[18]

The battery mathematical equations are done in MATLAB/Simulink using a simple regulated voltage source connected in series with a constant resistance, and obtained from[19]. The following equations, which are schematically shown in Fig. 3, explain the mathematical modelling.

$$E = E_O - K\frac{Q}{Q-\int idt} + Aexp(-B\int idt\,) \quad (7)$$

$$V_{batt} = E - RI_{batt} \quad (8)$$

Where,

Voltage exponential (V) = A

B = Accumulative capacity (Ah1)

V_{batt} = Nominal battery voltage (V)

Internal resistance is denoted by R_{batt}.

Battery current is denoted by I_{batt} In amps.

Technical details of BESS[12], [13], [14], [15]

Standard voltage	12 V
Standard capacity	2.57 KWh
Maximum capacity	260 Ah
DoD	80%
Roundtrip efficiency	90%
State of charge (SoC)	20

*The pricing shown is based on information gathered from regional Indian manufacturers and wholesalers.

3.4 Power converter

The capacity levels of converters are determined by the power that the converter will provide during peak demand hours and are stated in Eq. (9) [20]:

$$C_{cap} = (3L_{ind}) + L_o \quad (9)$$

where C_{cap}, L_{ind}, and L_O Respectively, stand for the converter capacity, total inductive loads, and total

other loads. Refrigerators, fans, and other inductive loads fall under this category, but LED lights, phone chargers, TVs, and other devices come in other load categories.

3.5 DC Micro Grid

In the proposed hybrid renewable energy system, both the solar photovoltaic (PV) array and the hydrogen fuel cell (HFC) function as DC power sources and are linked to a DC-link capacitor through a boost converter. Additionally, a battery bank, also serving as a DC source, connects to the DC link using a bidirectional converter.[1]

4. Experimental Proposed System

Table 1. Solar PV, Battery and Fuel Cell Components and Ratings

S NO	Component	Specifications
1	Solar PV Emulator	1KW
2	**Bidirectional Converter** ➢ V_{input} ➢ V_{out} ➢ I_{output} ➢ $F_{switching}$ ➢ IGBT ➢ IGBT Gate Driver ➢ Inductor ➢ Capacitor ➢ Resistance ➢ Snubber Capacitor	 100 V (Battery Side) 150 V (Inverter Side) 10 A 10 kHz SKM150GB12T4 SKYPER 32 R 3mH, 10A 4700mfd, 450V 27K, 20W 1 mfd, 1000VDC
3	**Single-Phase Bridge Rectifier (MB3514)** ➢ Rating ➢ Capacitor	 35A, 450V 417µF, 450V
4	**Three-Phase Inverter** ➢ Type ➢ V_{input} ➢ $V_{ac\ output}$ ➢ I_{output} ➢ $f_{Switching}$ ➢ f_{fund} ➢ IGBT ➢ IGBT Gate Driver ➢ Capacitor ➢ Resistance Snubber Capacitor	 3 Leg inverter 150V DC 112 V AC 25 A 10*k*Hz 50Hz SKM150GB12T4 SKYPER 32 R 4700mfd, 450V) *2 (20K, 20W) *2 1 mfd, 1500VDC
5	**Battery Bank (Lithium-ion)** ➢ Voltage ➢ Capacity Total No. Of Batteries	 72 V 30 Ah 1
6	**Autotransformer Three Phase (For Motor)** ➢ VImax	 0-450 V,15 A
7	**Autotransformer Three Phase (For Grid)** ➢ Voltage Range ➢ Max. Current	 0-450 V 8
8	**Grid Side MCB**	10 A (4 Pole)
9	**Type of the fuel cell: Proton Exchange**	**Type of the fuel cell: Proton Exchange**
	Number of cells	48
	Maximum stack temperature	65°C
	Performance	28.8 V and 35 A
	Flow rate at maximum output	13 Litres per minute
	Rated power	1000 W
	Reactants	Hydrogen and air
10	**Field-Programmable Gate Array (FPGA) Box**	
	Pull-up card for inverter gate	8 Pulse-Width Modulation (PWM) signals
	Control card technology	FPGA



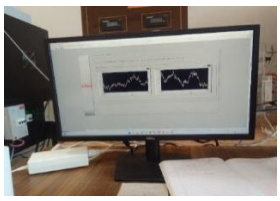
1. Rectifier and Converter



2. Battery (Li-ion)



3. Fuel cell



4. System setup



5. Solar PV

Fig.4. The HRES hardware configuration in the laboratory: Battery stack, converters and inverter configuration, and FC and PV emulator linked to the system.

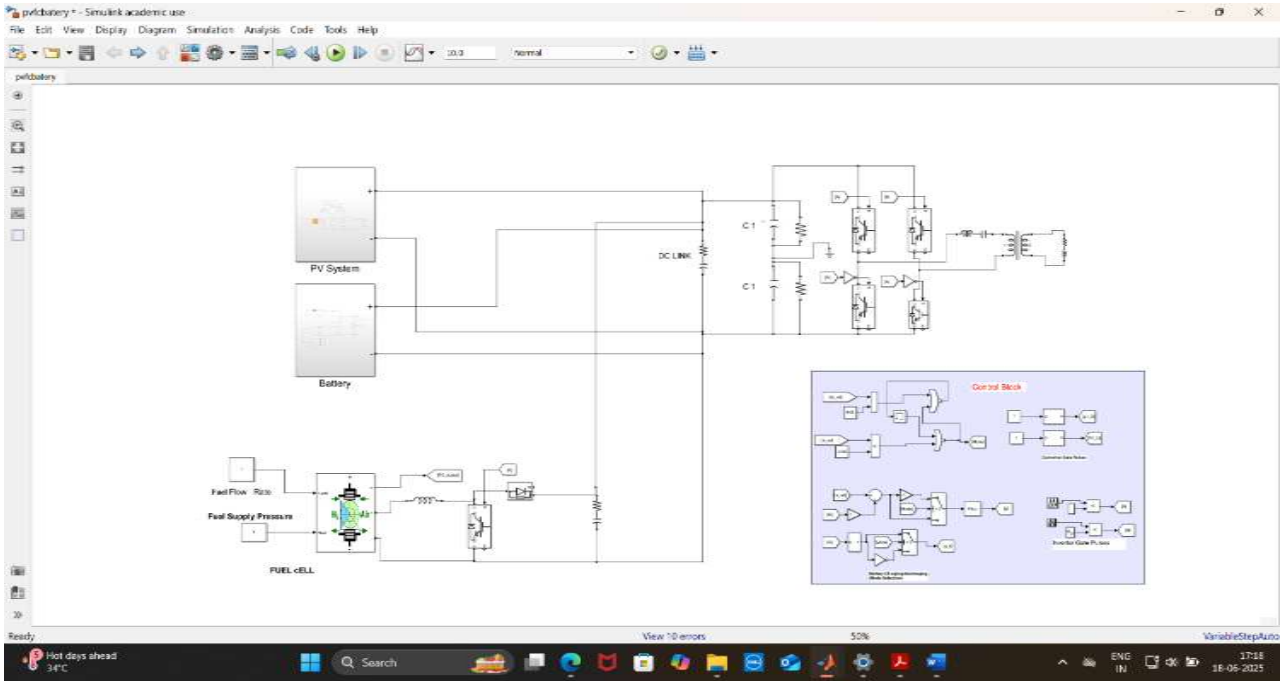
4.1 Hardware Implementation

As illustrated in Fig. 4, the hardware implementation is conducted in a laboratory setting, taking into account varying solar irradiance and load demand scenarios derived from real-time data. This experimental setup is developed based on a previously simulated MATLAB model. The control of hardware components is executed using the LabVIEW environment, where a user-friendly and simplified control interface has been designed. Communication between the hardware and the control system is established via a LAN/Ethernet

connection linking a personal computer (PC) with an FPGA-based microcontroller.A streamlined and user-friendly control panel is created, and the hardware components are controlled inside the LabVIEW environment. A LAN/Ethernet connection is used to facilitate communication between a PC and an FPGA-based microcontroller that is part of the hardware configuration.

5. MATLAB Implementation

The MATLAB simulation setup, illustrated in Fig. 2, is constructed based on the mathematical modelling and equations (1) through (8), along with the system's schematic representation in Fig. 1. The component ratings used in the simulation closely correspond to those in the actual hardware configuration to ensure accuracy.



Data acquisition is handled via a LabVIEW-based analyser, and the recorded data is stored in an Excel sheet. These values are then visualised using a graph-plotting tool. A battery is employed to either store energy or meet demand fluctuations, operating in both charging and discharging modes as required. During these modes, the output voltage, current, and frequency are monitored in real time using a power analyser (HIOKI 3360 series).

6. Result Analysis

A comparative analysis, both quantitative and qualitative, between the MATLAB simulation and the experimental hardware results (as shown in Figs. 4 and 5 and summarised in Table IV) reveals several key observations:

- The battery's response to load variations is quick and efficient.
- The system maintains operational stability while meeting load requirements effectively.
- The output frequency remains within an acceptable ±5% tolerance range.
- The MATLAB model accurately replicates the real hardware system's behaviour, demonstrating that the designed setup can supply adequate power to operate an irrigation pump.
- According to Table 2, the battery integrated within the Hybrid Renewable Energy System (HRES) exhibits strong transient and steady-state performance.

One noted limitation is the system's ability to support only limited load capacities. However, this constraint can be addressed by upgrading component ratings to accommodate higher demands. Additionally, during non-irrigation periods, the HRES can be utilised to provide lighting for both agricultural fields and residential areas.

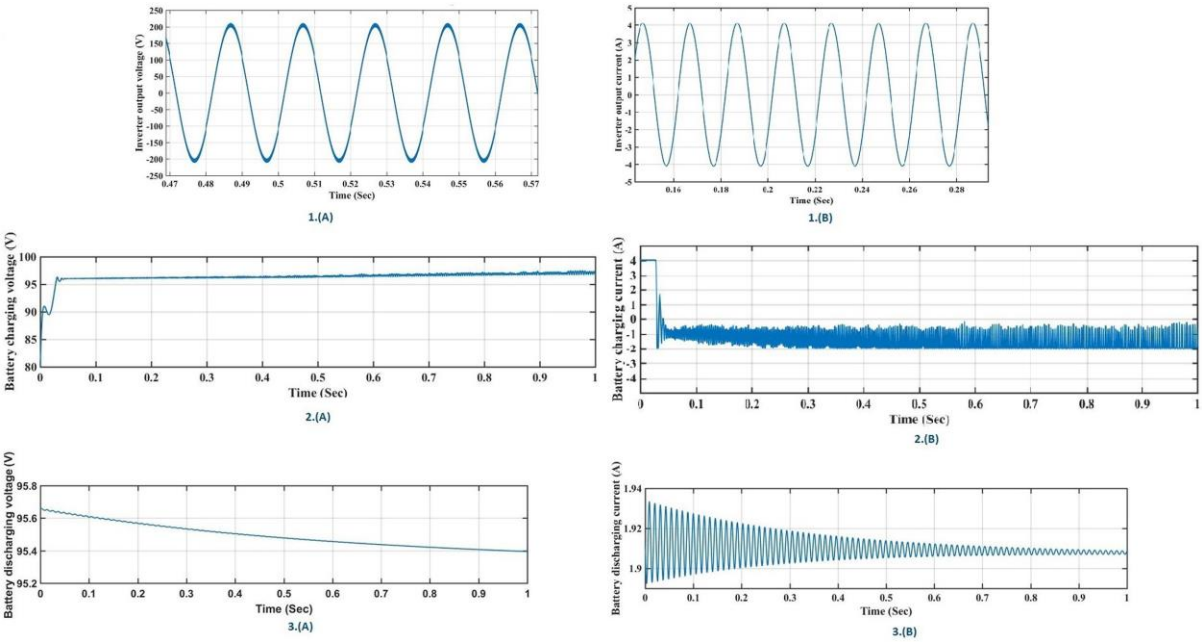


Fig. 6. The MATLAB simulation results for the Hybrid Renewable Energy System are presented as follows: Figures 1(a) and 1(b) illustrate the inverter's output voltage and current; Figures 2(a) and 2(b) show the battery voltage and current during the charging phase; and Figures 3(a) and 3(b) depict the battery voltage and current during the discharging phase.

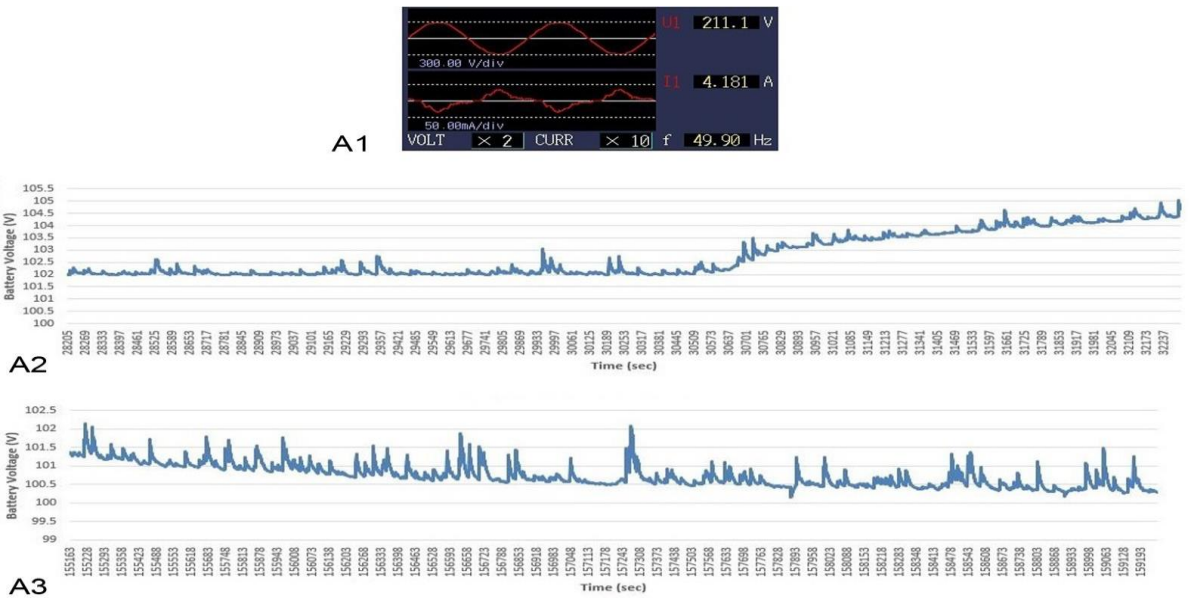
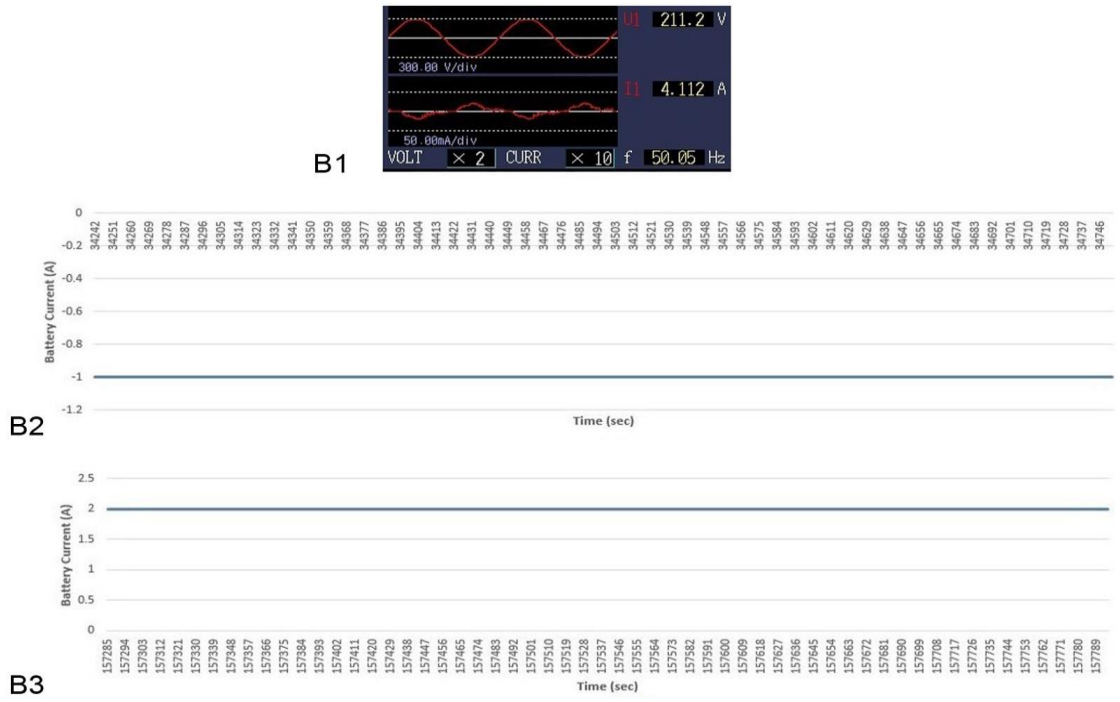


Fig. 7. The hardware results of the Hybrid Renewable Energy System are shown as follows: Figures 1(a) and 1(b) present the load-side output voltage, current, and frequency during the battery's charging and discharging cycles; Figures 2(a) and 2(b) display the battery voltage and current during charging; and Figures 3(a) and 3(b) illustrate the battery voltage and current during discharging.



4

Fig. 8. Additional results from the hardware implementation of the Hybrid Renewable Energy System are as follows: Figures 1(a) and 1(b) demonstrate the load-side output voltage, current, and frequency observed during both charging and discharging of the battery. Figures 2(a) and 2(b) depict the battery voltage and current during the charging process, while Figures 3(a) and 3(b) represent the battery voltage and current during discharging.

Table 2:The current signals of the battery are characterised by their step response.

Battery Current During Charging		
	Hardware Results	Simulation Results
Overshoot	0.02	0
Peak (A)	0.83	1
Settling time (s)	0.752	0.001
Undershoot	2.3	0
Rise time (s)	0.281	0.001
Battery Current During Discharge		
	Hardware Results	Simulation Results
Overshoot	1.85	2
Peak (A)	0.79	1
Settling time (s)	0.93	0.001
Undershoot	0.87	0
Rise time (s)	0.191	0.001

7. Conclusion

Any crop may be grown in paddy fields using the PV/FC/BESS hybrid power system, which was created and modelled for irrigation purposes. This hybrid system uses LabVIEW to regulate activities while operating in a standalone mode. The dynamic behaviours of the hybrid system have been examined under situations of varying solar radiation and load demand, using data on solar radiation and power demand derived from actual records. The created system's LabVIEW-based control method performs very well, even over lengthy periods.

8. ACKNOWLEDGMENT

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