Research Article

Kumaril Buts*, Lillie Dewan and M. P. R. Prasad

Development of renewable energy-based power system for the irrigation support: case studies

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Abstract: The development of renewable energy-based applications is nowadays a forced demand of society, for chasing the target set by the governments and the concerned organizations, to reduce or limit the carbon penetration in the environment. Sincere efforts are being made by academics and researchers to create applications based on renewable energy that are reliable and efficient. Green revolutions increase agricultural fields and alter grain production rates, but they also increase energy consumption since agricultural machinery is used more efficiently, mostly for irrigation needs. The purpose of this work is to introduce a hybrid renewable energy system (HRES) that can take the place of the diesel pump often used for time-bound crop irrigation. This HRES system consists of a photovoltaic generator as the main power source supported by a battery energy storage system. For this hybrid system, the development of a Proportional & Integral (PI)-based integrated hybrid controller is proposed to regulate the charge/discharge cycle of the battery energy with maintaining the load demand simultaneously. Controlling of this hybrid system is carried out in the LabVIEW environment.

Keywords: battery supported photovoltaic system; crop water management; hybrid renewable energy system; integrated hybrid control; irrigation pump

1 Introduction

Continuous energy is desired to develop and propagate any modern human development sector, and green energy supply is a forced demand of this present era.

***Corresponding author: Kumaril Buts**, Department of Electrical Engineering, National Institute of Technology, Kurukshetra, 136119, India, E-mail: kumaril_61900052@nitkkr.ac.in. https://orcid.org/0000-0003-3296-8510
Lillie Dewan and M. P. R. Prasad, Department of Electrical Engineering, National Institute of Technology, Kurukshetra, 136119, India, E-mail: l_dewan@nitkkr.ac.in (L. Dewan), mprprasad@nitkkr.ac.in (M.P.R. Prasad)

The recent data available, the agriculture field needs 4 to 8 percent of the total energy demand (IRENA and FAO 2021). In the context of the Indian agriculture sector, total electricity consumption during 2019–20 was 17.67 % with a 6.92 %-year wise growth (the base year 2018–19). Apart from the electricity consumption (228172 GWh), it also includes 628 metric tonnes (738,823.53 L) of diesel used during the year 2019–20 mainly for irrigation support.

The agricultural sector is distinct because it requires 4 to 8 percent of the total energy demand and is vulnerable to energy demand (IRENA and FAO 2021).

Apart from rainwater, farmers are dependent on other irrigation methods. One method for displacing the water from a deep-dug well is a diesel pump. Diesel pumps are expensive and harmful to the environment and ecological system.

For irriga/tion, a hybrid system based on renewable energy can give a consistent power supply at the necessary load level.

The wind system, photovoltaic (PV), fuel cell, natural gas-based plant, and battery energy storage system (BESS) are a few examples of renewable energy genres that are well-established and benefit from advanced technology.

The use of photovoltaic (PV) technology is advantageous where sunshine is abundant but with little or no grid assistance. To lessen the demand for coal-related electricity, PV generators are now installed even in grid-tied distribution zones.

A PV system's ability to produce electricity depends heavily on the availability of sunny days. A PV system must be combined with alternative backup power sources, such as Fuel Cell (FC) systems, Supercapacitor (SC) banks, or Battery Energy Storage Systems (BESS), for reliable operation on overcast days or at night.

For low-cost irrigation support, integrating the PV generator with a battery storage system is practical and reliable.

2 Literature review

Numerous studies and pieces of literature have been published on the integration of renewable energy sources, control strategies, and their applications in the domains of irrigation and/or farm equipment.

Even though renewable-based appliances are a cost-effective project, users do not always support the substitution of carbon-based energy demand with renewable energy. The requirement-based methodology is an effective strategy.

The use of a supercapacitor as an energy storage device for microgrid renewable energy systems is evaluated by Qusay et al. (2022). In this case study, the author discovered that charging the supercapacitor only with renewable energy sources can significantly improve the self-consumption of energy. Additionally, by adding a small amount of rapid-response energy storage, the system's average annual self-consumption for the investigated load increases in comparison to the system without energy storage.

Community-based Food-Water-Energy (FEW) nexus approaches are presented by Whitney et al. (2019) to optimize food, energy, and water security at the regional and global scale. This approach is implemented in the local fish industry.

Oumaima et al. (2022) studied the technical and financial aspects of photovoltaic installations for self-consumption as well as the installation of solar streetlamps to improve the performance of nocturnal lighting in Kenitra, Morocco, to lower the energy bill of the two institutions: the National School of Applied Sciences (ENSA) and National School of Commerce and Management (ENCG). The author made the argument that this technology will eventually enable real-time, remote control of load usage for improved comfort without sacrificing energy bill reduction.

Zhang et al. (2018) has implemented a photovoltaic-based application for the treatment of wastewater containing Nickel by electrocoagulation process using solar irradiation intensity (SII).

A PV system for irrigation applications in non-grid-supported remote rural areas for small-scale applications in Iran has been discussed by Ghasemi-Mobtaker et al. (2020).

Maka et al. (2022) analyzed the solar water pump design for remote, desert, and rural places where the electric grid connection is problematic. The author examined the design of the solar water pump system and predicted performance under actual environmental circumstances in this research. A system that enables an examination of the operational behavior of a photovoltaic solar water pumping system has been designed and simulated using the PV system.

Control operations carried out in the LabVIEW environment are currently receiving more attention than those carried out on other software platforms. Some of the built-in characteristics of the LabVIEW environment include simple operation and real-time data accessibility.

Bendib, Belmili, and Boulouma (2018) presented the photovoltaic generator characteristics in the LabVIEW environment and suggested some inherent technical advantages for controlling the hybrid system in the LabVIEW environment.

A Plethora of research work has been reported regarding renewable-based power applications, home appliances, farm machinery, and especially irrigation support in remote rural areas.

However, no one research article has yet been reported concerning the irrigation system design according to the specific crop needs.

Thus, this research paper presented for the very first time a renewable-energy-based irrigation system designed according to the crop requirement. This proposed system is capable to work day-night and in all-weather to fulfill the time-bound irrigation support.

The proposed PV and battery storage-based hybrid system is simulated in MATLAB at first and then implemented on the hardware available in Advance Power System Lab (APS), NIT Kurukshetra India in the LabVIEW environment, tested with varying solar radiation.

The paper is organized into six sections: after a brief introduction in section one, section two covers the related field's literature review. Section three describes the field study and the problem statement. Section four covers the system description with a short idea about the PV system, the battery energy storage system, the DC microgrid, and their controlling techniques, respectively. Section five deals with the controller design and the hardware development followed by a conclusion in section six and references (Figure 1).

3 Problem statements

The water requirement of the crop is calculated using simple water balance models (Aryal 2012; Bouman 2009), which include different inflows and outflows of water in the crop, as shown in Figure 2.

$$\mathrm{ER} + I = \mathrm{ET} + E + P + S + \mathrm{SD} + \mathrm{CWS} \quad (1)$$

where, ER: effective rainfall, I: irrigation supply, ET: evapotranspiration loss, E: evaporation loss, P: Deep percolation loss, S: seepage loss, SD: surface drainage or run-off loss, and CWS: changed in water status.

From Equation (1), it is clear that if effective rainfall is not available, water balance solely depends on irrigation.

Case Study I. Irrigation support for the rapeseed-mustard crop.

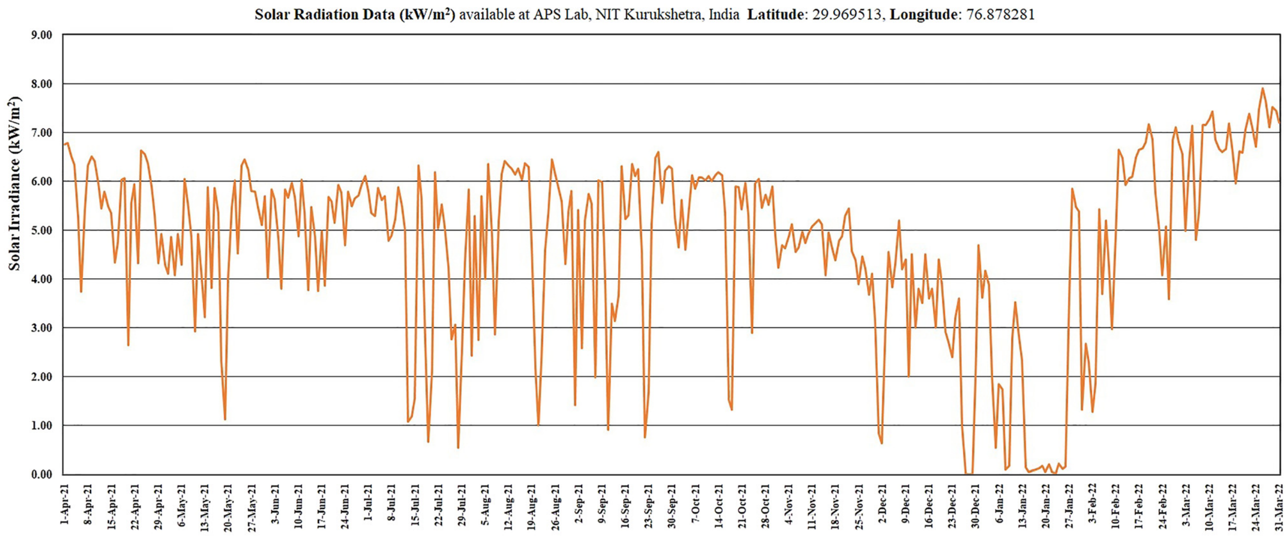

Figure 1: Solar radiation data for the simulation and hardware work.

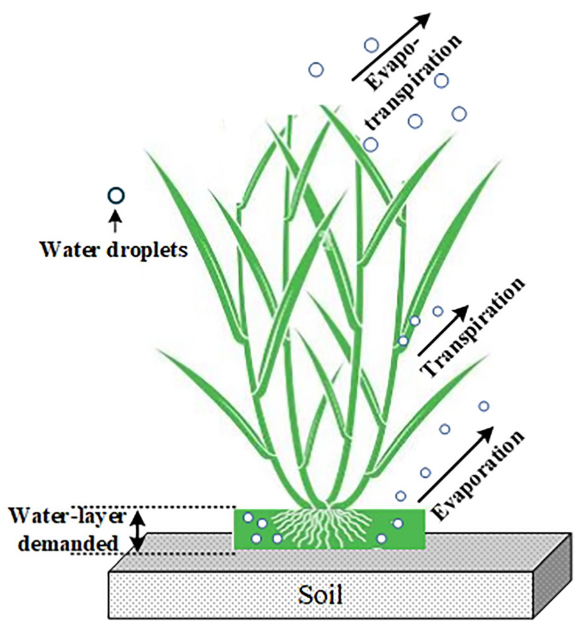

Figure 2: Water balances (inflows and outflows) of a typical crop.

Site location: Bharatpur, India (27.0150 N latitude and 77.0300 E longitude, 178.37 m above mean sea level).

Of all agricultural products produced globally, vegetable oil accounts for one of the biggest production shares (40 percent). India mostly cultivates oil seeds on marginal lands that are dependent on monsoon rainfall (unirrigated) and use low input levels. Rapeseed mustard is a significant crop among oilseed crops, and India ranks third globally in this regard. It is mostly grown in rainfed ecosystems with the help of stored monsoonal rainwater and a few wintry showers, and it is confined to Rajasthan (one state in the nation), which is in the country's northwest, for 50 % of its total area.

Rapeseed mustard can support a large number of farmers' livelihoods with effective crop management in these regions. To effectively utilize the limited moisture available during the crop season, particularly at crucial times of crop growth and high evaporative demand (2–6 mm per day), sound management strategies for rapeseed mustard are required (Rathore et al. 2019).

In general, irrigation is used during crop time in mustard-growing regions. By adding irrigation water and rainfall, the total amount of water applied (input water) was calculated. The entire water balance was calculated considering the input of irrigation water from rainfall and water productivity.

At the pre-flowering and pod-filling stages, the mustard leaf's relative water content (RWC) was evaluated. Based on the leaf's fresh, dry, and turgid weight, the RWC is approximated in percent. The equations for Relative water content (RWC) and soil moisture dynamics were used to calculate various growth, water productivity, and energy factors.

Table 1 lists the weather conditions that prevailed during the crop's growing season.

Case Study II. Drip-mulch irrigation for tomato crop.

Site location: East Sikkim District, Sikkim, India (27.330 N latitude and 88.60 E longitude, 1650 meters above mean sea level).

Because of its high nutritional value, extensive production, and widespread use as a vegetable, tomatoes are regarded as one of the most productive and protective foods.

It is produced in a broad variety of climatic conditions throughout India, which is the world's second-largest producer after China (Reddy et al. 2018). It is a warm-season crop, and drip.

Irrigation and moisture conservation with different mulches are thought to improve water use efficiency and help farmers accomplish their main goal of "more crop per drop." Due to its accurate and direct distribution of water to the root zone and significant irrigation water savings, drip irrigation is widely used, particularly for fruit and vegetable crops. The amount of irrigation needed was calculated by subtracting the projected value of ETc from the effective and predicted (80 %) rainfall. At an average pressure of 0.3 kg/cm^2, it was discovered that the average discharge per dripper was 1.24 lph.

The treatment, which used drip irrigation along with mulch instead of the control, saved 62 percent of irrigation water. As water is sprayed immediately near the crop's root zone in the needed quantity, water loss due to percolation, runoff, seepage, and soil evaporation may be reduced, increasing WUE and saving irrigation water under drip irrigation with mulch.

As a result of the current study, it can be said that using mulch and drip irrigation together significantly boosted both yield and WUE.

The study of case-I and case-II, reveals that the water requirement from the initial to the late season (as given in Tables 1 and 2), an irrigation pump of the capacity shown in Table 3, will be sufficient for the time-bound irrigation support of the crops.

The advantages of this system include its reliability, efficiency, and affordability for time-bound irrigation support of the crops.

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

Table 1: Monthly average weather conditions during the crop-yielding period (The year 2020–21).

Months	Average temperature (Deg. C)	Average rainfall (mm)	Evaporation (mm/day)
October	32.1–34.6	30.8	3.6
November	27.9–30.2	6.0	2.0
December	22.4–20.6	13.3	1.2
January	17.0–16.9	55.7	0.4
February	21.6–25.9	10.4	2.1
March	29.4–28.7	13.8	2.3

4 System descriptions

This proposed hybrid system contains a photovoltaic generator and a stack of battery systems. The line diagram of this proposed hybrid system is shown in Figure 3.

As shown in Figure 3, the PV generator is connected to a boost converter, and the battery system is attached to a bidirectional buck-boost converter. Both the converter is joined at the DC-link capacitor.

4.1 The PV system

The photovoltaic effect is the illumination of two different materials' common connections by photon irradiation that results in electrical potential. With single and two-diode models, the electrical characteristics of a PV system can be represented. Popular and accurate, the single diode model represents how PV cells behave.

The mathematical modeling of the PV system output voltage can be described as follows using the single diode model: (Buts, Dewan, and Prasad 2020).

$$V_{\mathrm{PV}} = \frac{N_S nkT}{q} \ln\left[\frac{I_{\mathrm{SC}} - I_{\mathrm{PV}} + N_P}{N_P I_0}\right] - \frac{N_S}{N_P} R_S I_{\mathrm{PV}} \quad (2)$$

where, N_S: the number of series cells per string, n: ideality factor, k: Boltzmann's constant [J/deg K], T: PV cell temperature [deg K], q: electronic charge [C], I_{SC}: short-circuit cell

Table 2: Estimated water requirement for different growth stages of tomato.

Crop stage	Duration (Day)	K_C	ETo	ETa	Dripper discharge (L/h)	Time of operation over 2 days (in minutes)
Initial	20	0.46	2.46	1.13	3.5	9.30
Development	30	0.83	2.05	1.70	3.5	13.98
Mild season	40	1.08	3.14	3.39	3.5	27.90
Late season	25	0.86	3.87	3.32	3.5	27.31

K_C, crop coefficient; ETo, evapotranspiration; ETa, actual crop evapotranspiration.

Table 3: Performance of a typical 0.5 hp single-phase irrigation water pump.

Specifications	Descriptions
Power rating	0.5 HP (0.37 kW)
Full load current	2 A
Rated voltage	210 V
Water head	4 m
Discharge	15.5 L per sec (LPS)

current [A], I_{PV}: PV cell output current [A], N_P: the number of parallel strings, I_0: PV cell reverse saturation current [A], and R_S: series resistance of the PV cell [Ω].

4.2 Battery energy storage system (BESS)

A stack of cells connected in series or parallel to supply the required voltage or current level is referred to as a battery energy storage system (BESS).

The two distinct formulae for the charging and discharging modes are used individually to calculate the battery voltage, V_{Batt}. Equations (3)–(5) were used to model the battery's characteristics mathematically (Fan et al. 2018).

$$V_{Batt\,(charge)} = V_O - \frac{KQ_{max}}{0.1Q_{max} - q} i^* - \frac{KQ_{max}}{Q_{max} - q} it + A\exp(-Bq) \quad (3)$$

$$V_{Batt\,(discharge)} = V_O - \frac{KQ_{max}}{Q_{max} - 1} i^* - \frac{KQ_{max}}{Q_{max}} it + A\exp(-Bq) \quad (4)$$

where, V_O: the battery's constant output voltage [V], K: the polarization constant [(Ah)$^{-1}$], Q_{max}: the battery's maximum capacity [Ah], i^*: reference current [A], i: measured (actual) current [A], q: battery's available capacity [Ah], A: exponential voltage [V], and B: exponential capacity [(Ah)$^{-1}$].

The state of the charge of the battery (SOC_{Batt}) is calculated as:

$$SOC_{Batt} = 100\left(1 - \frac{\int i(t)dt}{Q}\right) \quad (5)$$

where, i: instantaneous current [A], and Q: charge stored [C].

4.3 DC-link

Through their respective converters, the solar PV system and battery system serve as a DC source and are coupled to the DC-link capacitor.

Figure 4 illustrates how the PI controller maintains the DC-Link voltage.

4.4 Power converters

In the suggested system, the bidirectional buck/boost converter is linked to the battery stack for charging and discharging phenomena, respectively, and the boost converter is connected to the PV generator.

Between the DC link and the single-phase transformer lies a single-phase inverter. The most effective and trustworthy method of managing the power converter is pulse width modulation (PWM) (Hole and Goswami 2022; Shayegh et al. 2021).

This method is employed to regulate the inverter's frequency as well as the converters.

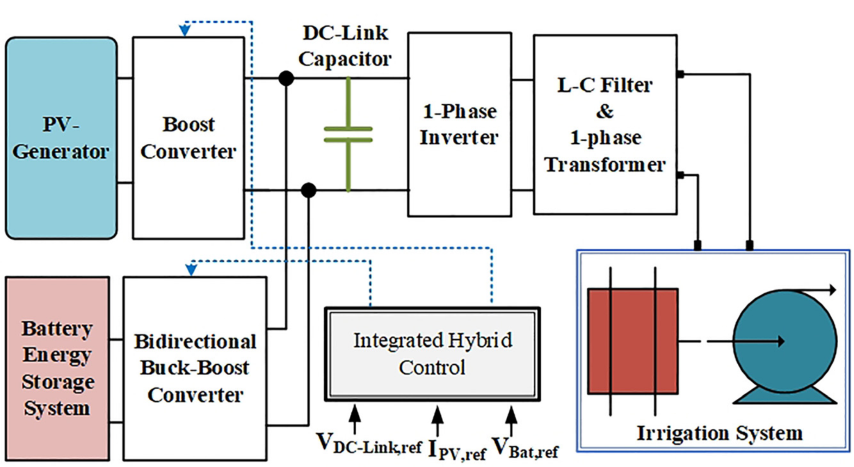

Figure 3: Line diagram of the hybrid renewable energy system (hybrid RES).

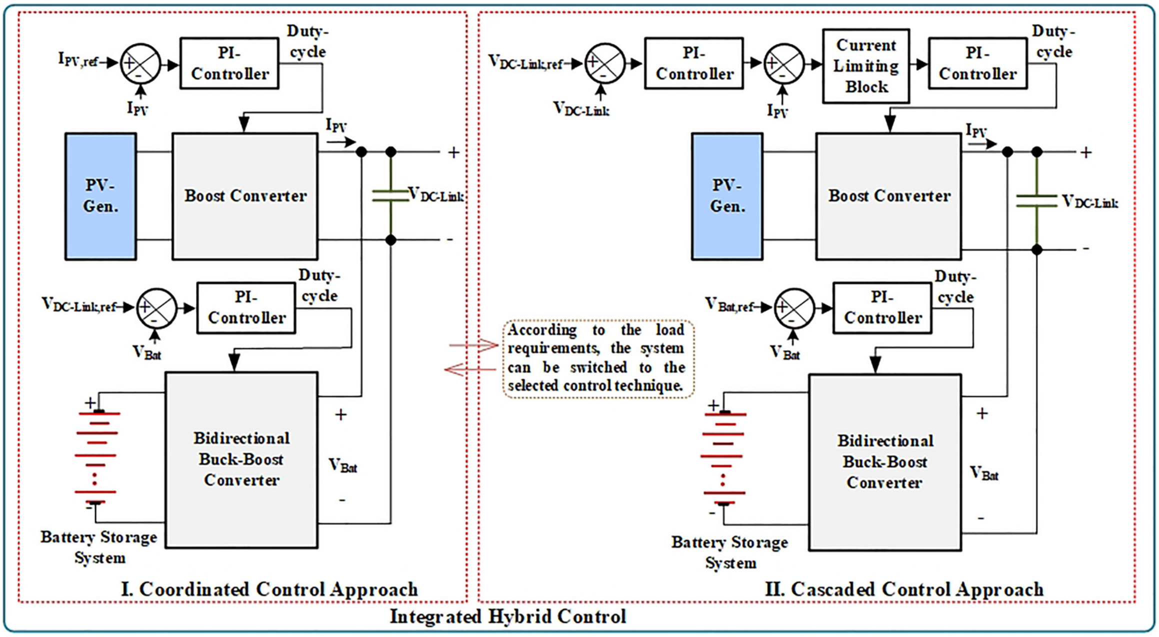

Figure 4: PI-based integrated hybrid controller.

4.5 Controller design for PV-BESS power management

A PI-based hybrid controller is proposed for the power management of this hybrid system. This hybrid control approach regulates the load current by maintaining the load voltage at the desired level and ensuring the battery charging/discharging cycle is proper. The working of this hybrid controller is shown in Figure 4.

As shown in Figure 4, the outer loop of the controller which is associated with the battery storage system, maintains the battery voltage, while the inner loop regulates the battery current. The load voltage of the system is maintained by maintaining the DC-Link voltage.

The working principle of this hybrid controller is, that when the PV system generates more power than the load demand then this surplus power is stored in the battery storage system; and when there is less power or no power

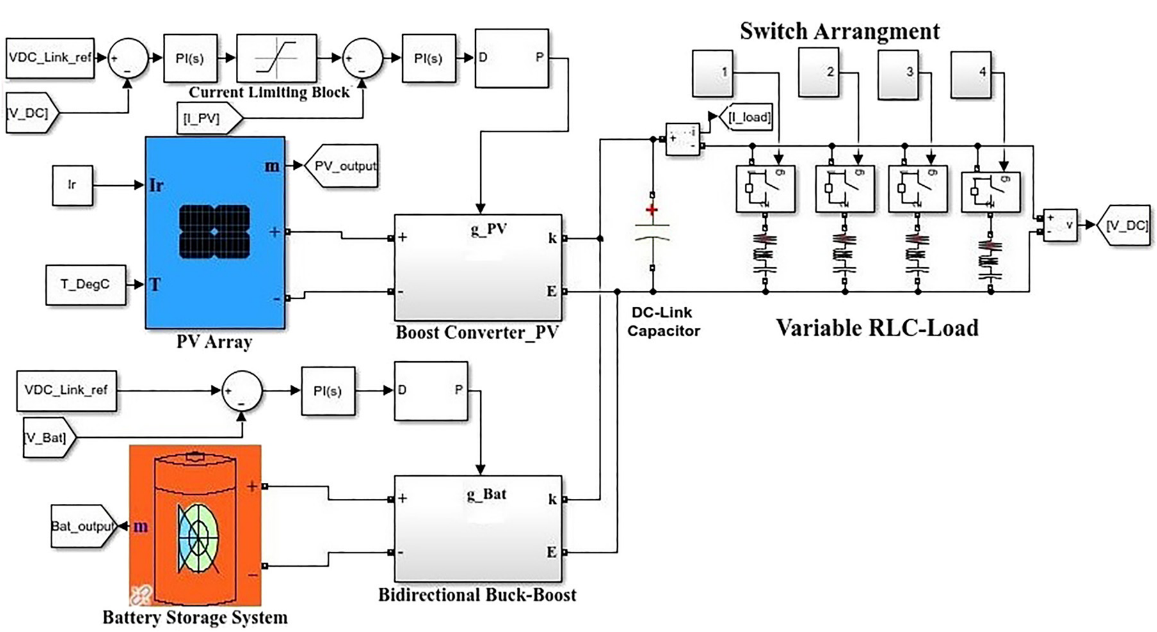

Figure 5: MATLAB simulation block-set and results of the proposed HRES. (a) MATLAB simulation block-set, (b) MATLAB simulation results.

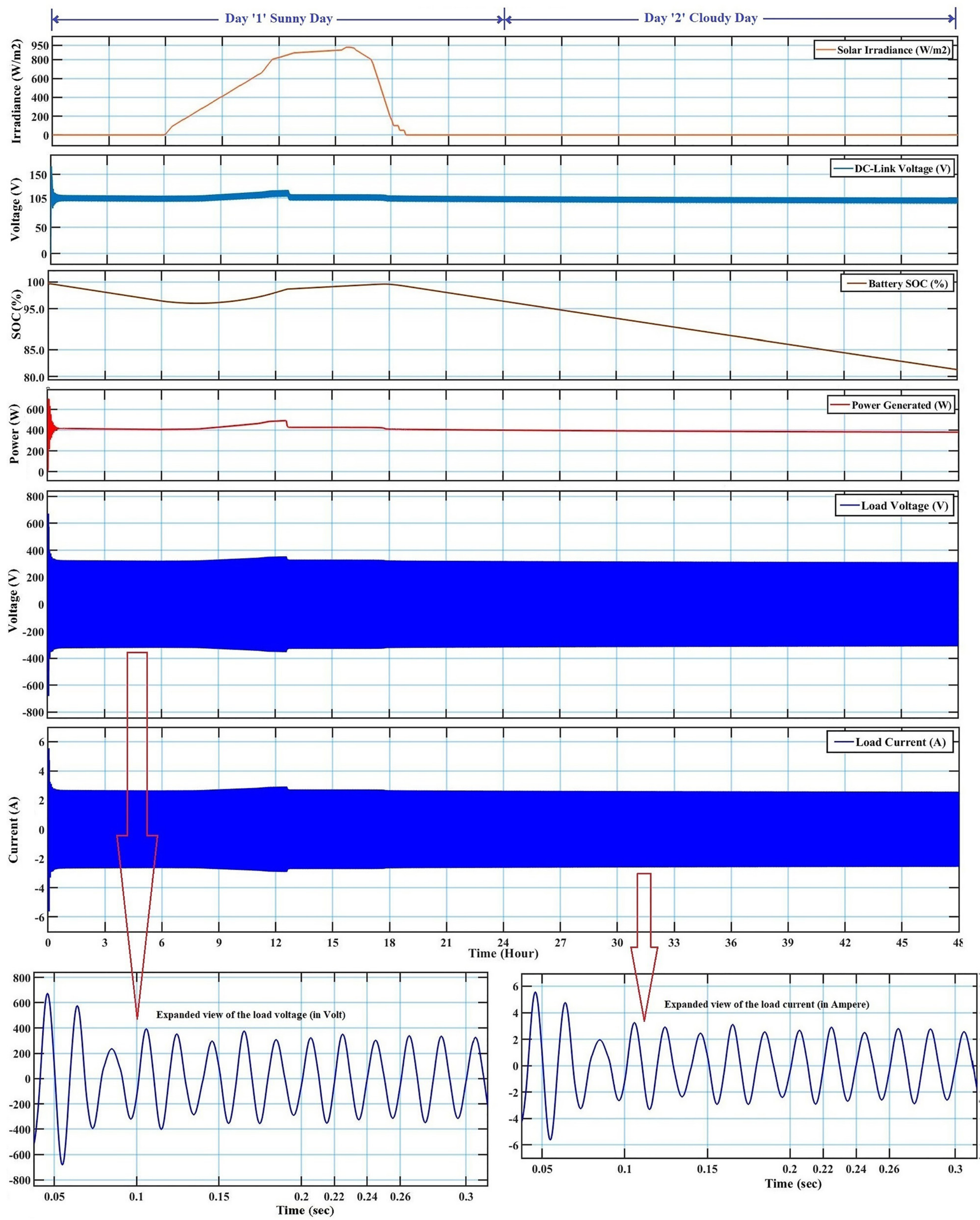

Figure 5: Continued.

Table 4: Essential parts & specifications of the hardware setup.

Sr. no	Components	Specifications
	Controller parameters	
1.	Control card technology	FPGA
2.	Pull-up card for inverter gate firing	8 PWM signals
	Single-phase inverter	
1.	DC input voltage	150 V
2.	Output voltage, & current	112 V, 4 A
3.	Switching frequency	10 kHz
	LC filter for the inverter	
1.	Inductor	3 mH, 10 A
2.	Capacitor	10 μF
	PV specifications and ratings	
1.	Short-circuit current, & open-circuit voltage	20 A, 50 V
2.	Maximum output power	1 kW
	Boost converter for PV system	
1.	Input voltage, & current	50 V, 20 A
2.	Output voltage, & current	150 V, 10 A
3.	Switching frequency	20 kHz
	Battery storage system	
1.	Battery type	Lithium-ion
2.	Output voltage, & capacity	72 V, 30 Ah
	Bidirectional buck-boost converter for battery	
1.	Voltage, & current	105 V, 10 A
2.	Switching frequency	20 kHz

available from the PV source then the battery energy system injects sufficient power to the system for maintaining the load demand.

Accordingly, two cases are arising, first when the PV current is more than the load current, and second when the load current is more than the PV current; i.e.,

Case 1. When $I_{PV} \geq I_{Load}$

In this situation, the battery stack goes to charging mode.

Case 2. When $I_{PV} < I_{Load}$

In this situation, the battery stack injects power into the system.

5 Implementation

The proposed hybrid system is first simulated on MATLAB-Simulink R2021b and then implemented on the hardware available in the Advance Power System Lab, NIT Kurukshetra, India, in the LabVIEW environment.

5.1 MATLAB implementation and results

The line diagram of the system illustrated in Figure 3 and the mathematical modeling described in equations (2)–(5) are the foundations for the MATLAB model as shown in Figure 5(a). MATLAB simulation results are shown in Figure 5(b). As with the hardware configuration, precise ratings of the MATLAB components are taken, as seen in Table 4.

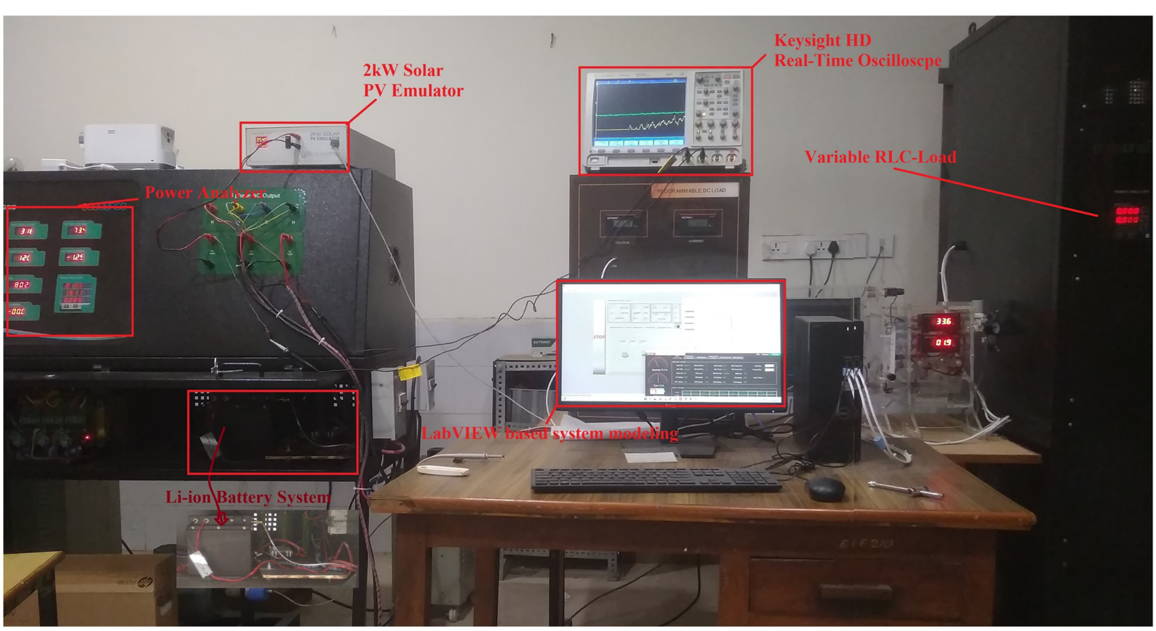

Figure 6: Hardware implementation and results of HRES. (a) Hardware setup of the hybrid system, (b) hardware results.

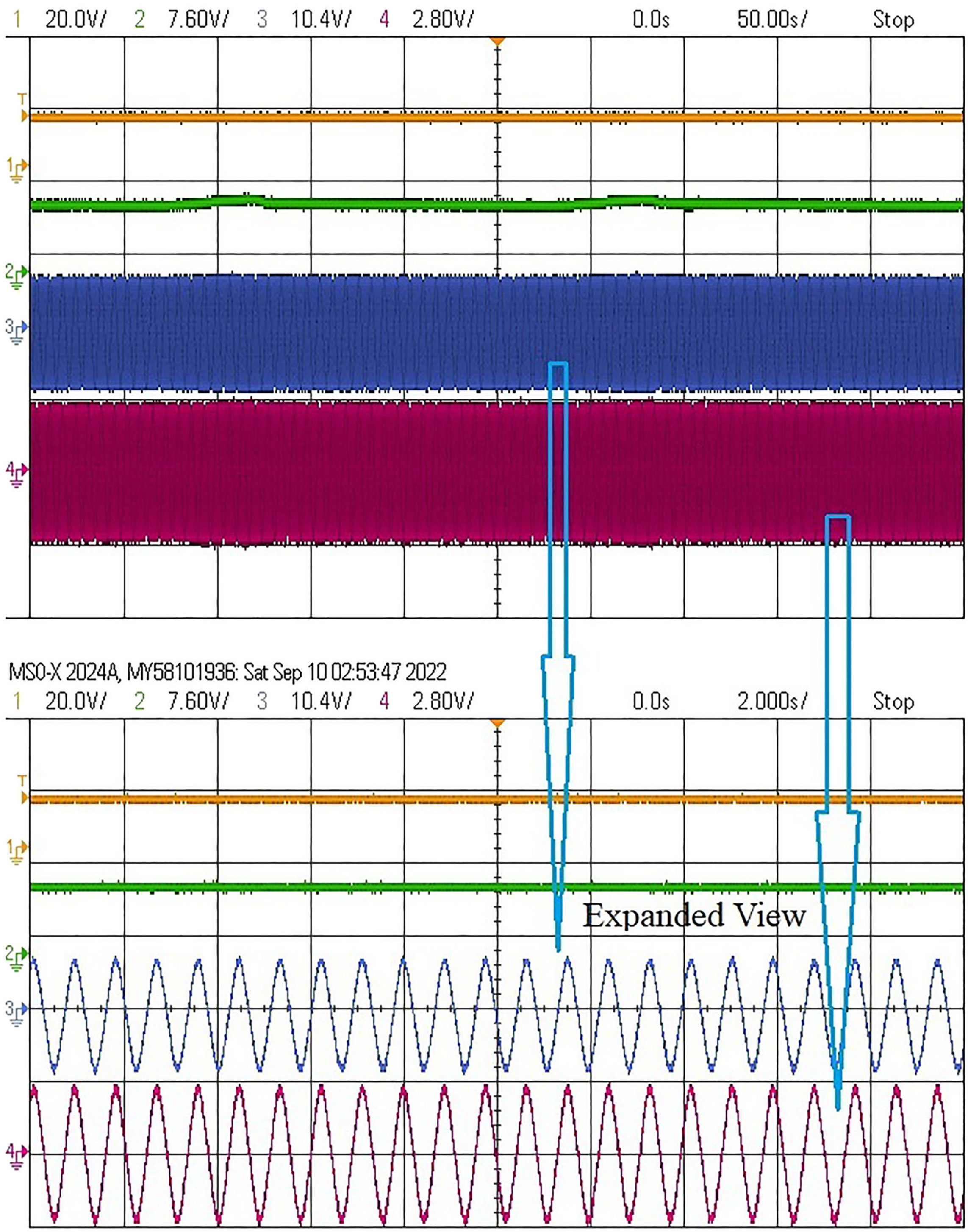

Figure 6: Continued.

5.2 Hardware implementation and results

The suggested hybrid system maintains the load demand with fluctuating solar irradiation by simultaneously maintaining the load voltage and the battery charging/discharging cycle, as can be seen from the MATLAB-Simulation results, as shown in Figure 5(b). Hardware implementation is carried out in the lab using the MATLAB model, as illustrated in Figure 6(a).

The hybrid system's hardware configuration consists of a battery stack, a solar PV emulator, power converters, and controllers with an FPGA architecture.

IGBT-based power switches are employed for the converters' hardware implementation to provide quick and dependable operation.

With the aid of the Field Programmable Gate Array (FPGA) based PWM controlling technology, the hardware components are controlled in the LabVIEW environment.

With the aid of VHDL (Very High-Speed Integrated Chip Hardware Description Language) physical architecture, an FPGA-based micro-controller chip is employed in this hybrid system to generate and control the gate pulses.

The PI-based hybrid controller is implemented in VHDL code for the PWM control. The modified gate pulse controls the output of the converters.

Using a personal computer, the user can control the gate pulse (PC). Through a LAN/Ethernet cable, the PC connects with the FPGA-based microcontroller.

The hardware results of the hybrid system are shown in Figure 6(b).

The MATLAB and Hardware results of the hybrid system are obtained with the varying solar irradiance data, available in the APS Lab, as shown in Figure 1.

6 Discussions

The system is tested with the real local solar irradiance data, as shown in Figure 1, and the actual load demands.

The battery is run in charging/discharging mode for power storage or to lessen load demands. Output voltage and current with frequency are captured on a real-time high-definition oscilloscope (Keysight) during the battery charging and discharging time, respectively. According to the hybrid system's simulation results, which are displayed in Figure 5(b); the suggested system can provide all of the required power during the whole irrigation season without any interruptions. As illustrated in Figure 6(b); the hardware result replicates the proposed system's simulation result.

The following significant information is provided through comparative analyses of the hardware results and the MATLAB simulation:

i. During a load shift, the battery charges and discharges quickly and effectively.
ii. The system meets the desired load needs and is stable.
iii. Frequency is still within the permitted range with a tolerance of 5 %.
iv. It may be argued that the intended system can generate enough power to drive the irrigation pump because the behavior of the system's MATLAB model closely resembles that of the hardware setup in use.
v. This hybrid system is capable of offering sufficient irrigation support day or night and in any kind of weather.

Additionally, it can be inferred from the simulation and hardware findings that the PI-based hybrid controller enables proper power management by maintaining the load voltage and the battery charging and discharging cycle.

7 Conclusions

The hybrid PV-BESS power system was created and modeled for irrigation, but it may be used for any crop in addition to paddy fields. This hybrid system is working in standalone mode with controlling activity in the LabVIEW environment.

Under a range of solar radiation and load demand situations, the dynamic behavior of the hybrid system is examined. The data used to determine solar radiation and power demand are taken from historical records. The LabVIEW–based control strategy for the developed system is efficient and exhibits excellent performance over an extended period.

By altering the component ratings, this system may be made to handle the increased load requirement. This hybrid system can be used to farm equipment and used to light up peasants' homes during the off-irrigation time.

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