

Real-Time Implementation of Energy Management for Photovoltaic/Battery/Diesel Hybrid System Based on LabVIEW

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Abstract- This paper presented a complete design and simulation of a PV battery diesel hybrid system for supplying agriculture farming demands in remote areas. A power management subsystem for monitoring and controlling a PV battery diesel hybrid system (PVBDHS) was proposed. A simple monitoring system has been designed using LabVIEW Interface for the Arduino. LabVIEW program Interface for the Arduino (LIFA) was used to monitor PVBDHS parameters; DC bus voltage, PV current, battery current and load current power in real-time to overcome the data acquisition. The Arduino Uno microcontroller board was used as a data acquisition medium to collect data from the PVBDHS. The embedded control board based on the Arduino UNO board used a voltage sensor and current sensor at a low cost and the data are transmitted from the hardware to the LabVIEW program by using written interfacing software. Finally, a pilot plant of PVBDHS was implemented and tested. Different cases of system operation are tested. The results depicted that, as load demand changed, the energy management subsystem was able to change the batteries status according to SOC value and diesel status change sequentially. All modes of operation of proposed system gave the estimated response. Also, the results showed the ability of the energy management subsystem to monitor and control PVBDHS system operation with real-time conditions. The results were reliable and stable and prove the accurate function of system operation.

Keywords: Hybrid power systems; Photovoltaic; Power management; Embedded controller; LabVIEW; Arduino.

1. Introduction

The integration between renewable energy and conventional sources is to overcome the disadvantages of some sources by the others in a controlled way [1-3]. Hybrid renewable energy systems are now used to give electricity to rural and remote areas where the grid's extension is difficult [4-8]. Mostly of renewable energy systems used diesel generators as a backup source. Merging renewable sources with diesel generators is to compensate for drawbacks of each other [9-11]. Diesel generator has a high operating cost, high fuel transportation cost, and constant maintenance [12].

In developing countries, rural electrification is difficult and costly due to geographical and climatic conditions variation, so remote villages represent a high potential market for hybrid renewable power systems [13, 14]. Many

research papers studied the hybrid renewable energy systems from different points of view; design, techno-economic and feasibility, control, and monitoring. [15, 16] provided the best design, techno-economic, and feasibility research of hybrid and grid-connected systems using HOMER software. [17] evaluated the performance of PV/diesel/battery hybrid systems utilised in rural community applications in Bangladesh. Stand-alone PV/fuel Cell/diesel generator power system optimal design and economic comparison are carried out in [18].

The survey study discloses several microcontroller-based data acquisition systems for monitoring and performance evaluation of PV systems [19]. PV systems have been monitored using Laboratory Virtual Instrument (VI) Workbench (LabVIEW)-based monitoring systems [20–23]. LabVIEW is a graphical user interface, which supports data

acquisition, manual and automatic control of system parameters. LabVIEW developed by the virtual instrument, used in collecting and analyzing metrological data and PV system performance. LabVIEW allows the system designers to optimal control and management PV systems, moreover its ability to interact with MATLAB software [24]. A PV power plant in Bogota monitoring system is designed by using LabVIEW [25]. LabVIEW was used to conduct a feasibility analysis of a PV, wind turbine, and diesel generator system, as well as a supervision dashboard for monitoring system performance [26]. A PV diesel hybrid system's energy management technique is investigated, and an experimental setup is developed to evaluate system performance [27]. PV battery stand-alone monitoring system prototype using data acquisition is introduced in [28]. PV power plant performance has been studied by using the Virtual Instrumentation concept [29]. The real-time signal measurement gives information about the plant performance as well as the generated energy quality. Large-scale PV system performance and analysis have been presented [30]. Evaluate and analyze PV performance taking into consideration the effect of environmental conditions on PV characteristics. Electrical performance estimation of PV modules using measurement system has been studied [31]. [32] describes the monitoring and experimental setup for measuring metrological data and electrical PV-standalone system parameters. [33] shows a PV monitoring system built with LabVIEW and the Arduino IDE (software and hardware). For maximum system efficiency, [34] uses real-time monitoring of PV parameters and system performance, as well as a tracking system.

Authors of [35] discussed many aspects of data acquisition, interfacing, and programming-based hybrid system (PV, wind). In [36], a hybrid PV-diesel micro-grid system without energy storage control strategy control diesel engine speed, load voltage regulation, and PV maximum power point (MPPT) by a modified fuzzy logic controller (FLC) and pulse width modulation (PWM) control technique. A distance laboratory for real-time monitoring of a remote photovoltaic system within a few variables presented in [37, 38]. Sun simulator-based LabVIEW measures PV electrical characteristics in [39]. In [40], an on-site platform test was used to gather and evaluate the performance of the PV-grid connected system [41]. PV modules output parameters as voltage, current, and meteorological variables as module temperature, solar radiation, and air humidity were measured in real-time [42]. In addition, developing an educational tool platform to study photovoltaic performance in real-time was done. In [43], a detailed PV systems performance and characterization based LabVIEW in real-time is studied. Challenges in PV battery diesel hybrid system (PVBDHS) system operational control and monitoring are discussed in [44].

This paper presents a design of a PVBDHS for an agriculture farm in a remote area. A complete software program used for sizing, modeling, and energy management for PVBDHS based on LabVIEW is completely programmed. A prototype of an energy management system

for the PVBDHS system is designed and implemented. The real system design is based on a microcontroller board for acquisition, preprocessing, and transmitting data to a host computer, which is responsible for receiving, processing, management, and supervising using LabVIEW Application. The developed application includes several user controls and graph visualization that make it economic and powerful.

2. Hybrid Photovoltaic/Diesel/Battery System Configuration and Modeling

Figure 1 illustrates the PVBDHS block diagram that is considered in this study. The proposed PVBDHS involves PV arrays, batteries, a diesel generator, loads, a control unit, and a monitoring unit. The mathematical modeling of different components in PVBDHS is given below. These equations will be used in the system design, sizing, and simulation.

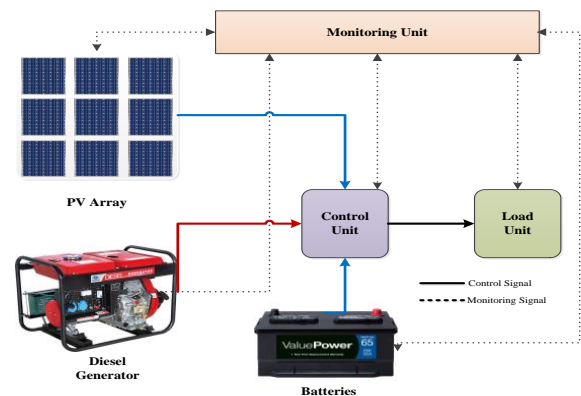


Figure 1. Block diagram of the proposed PVBDHS.

2.1. PV Mathematical Model

PV mathematical model describes the relation between PV current, power, and voltage based on the electrical behavior of the PV modules. The operating equation of current-voltage characteristics of solar cell under illumination effect is expressed by [45- 47]:

$$I_G = N_p I_{lg} - N_p I_o \left(\exp \frac{(V + I_G R_S)}{V_t} - 1 \right) \quad (1)$$

$$V_t = \frac{a k N_s T_{pv}}{q} \quad (2)$$

Light generated current is given as:

$$I_{lg} = \frac{G}{G_r} [I_{lr} + m(T - T_r)] \quad (3)$$

Where reverse saturation current of PV cell is represented by:

$$I_o = c T_{pv}^3 \exp \left(- \frac{q E_{go}}{b k T_{pv}} \right) \quad (4)$$

$$I_o = I_{or} \left(\frac{T_a}{T_p} \right)^{\beta_n} \exp \left(- b \left[\left(\frac{1}{T_p} \right) - \left(\frac{1}{T_r} \right) \right] \right) \quad (5)$$

$$I_{or} = \frac{I_{scr}}{\left[\exp\left(\frac{V_{ocr}}{V_{tr}}\right) - 1 \right]} \quad (6)$$

Cell temperature can be calculated by using the following equation:

$$T = T_a + \left[\left(\frac{\tau\alpha}{U_l} \right) \left(I - \frac{\eta}{\tau\alpha} \right) \right] G \quad (7)$$

Where I_G is output current of PV array (A), V is the output voltage of PV array (V), N_s is series modules number, N_p is parallel strings number, I_{lg} is light generated current (A), I_o is reverse saturation current at operating temperature (A), R_s is the series resistance, a is ideality factor, q is the electron charge, and T_{pv} is cell temperature (K), k is Boltzmann constant, G is cell illumination, W/m², G_r is reference illumination (1000 W/m²), E_{go} is band gap for silicon (=1.11 eV), m is short circuit current temperature coefficient (=0.00065 A/°C), U_l is heat transfer coefficient, I_{scr} is reference short circuit current, V_{ocr} is reference open circuit voltage, and $\tau\alpha$ is emittance absorptance product.

2.2. Mathematical Model of Diesel Generator

The rated capacity (P_{gr}) and the actual power delivered (P_g) at a certain time affect the fuel consumption of the diesel generator. The following equation is used for estimating fuel consumption (FC) in l/h as [48]:

$$FC(\Delta t) = A P_g + B P_{gr} \quad (8)$$

Where A is a constant equal to 0.2088 (l/kWh) and B is a constant equal to 0.01841 (l/kWh). The diesel generators' fuel consumption values within the capacity range of 150–1800 kW at 25, 50, 75, 80, and 100 % load are obtained in [49]. The DG efficiency (η_g) in kWh/l is given as:

$$\eta_g = \frac{1}{\left(\alpha + \beta \times \frac{P_{gr}}{P_g} \right)} \quad (9)$$

The efficiency of the lower heating value (LHV) of Gas-oil can be defined as follows [49]:

$$\eta_g \% = \frac{P(t)_g (kW)}{Q(t)(l/h) \times LHV_{Gas.oil} (kWh/l)} \times 100 \quad (10)$$

The specific fuel consumption is obtained as [49]:

$$sfc = \frac{\dot{V}_f}{P} \quad (11)$$

Where $LHV_{Gas-oil}$ is constant varies between 10 and 11.6 (kWh/l), sfc is the specific fuel consumption (l/kWh) represents the fuel flow rate per unit output power, which reflects how efficiently an engine is consuming the fuel to produce energy, \dot{V}_f is the volume flow rate (l/h), P is output power (kW). The value of reference volumetric flow rate is in the datasheet as a function of generator loading.

2.3. Mathematical Model of Battery

The lead-acid battery is used as a storage element for electrical energy in PV hybrid systems. The batteries function; regulate system voltage and feed load with the required power in cloudy days. The battery voltage is a function of open-circuit voltage and the voltage drop across the internal resistance of the battery (R_B) as [50, 51]:

$$V_B = V_r + I_B R_B \quad (12)$$

The rest voltage, V_r , is in terms of battery cell temperature as [50, 51]:

$$V_r = 2.04[1 - 0.001(T_c - T_r)] \quad (13)$$

Where V_B is the battery voltage (V), I_B is the battery current (A), T_r is the reference temperature, and T_c is the battery cell temperature.

The battery resistance during charge and discharge process is given by:

$$R_{BC} = \frac{I}{BC} \left[R_i + \frac{0.189}{(1.142 - SOC)} \right] + (SOC - 0.9) \ln \left(300 \frac{I_B}{BC} + 1 \right) \quad (14)$$

$$R_{BD} = - \frac{I}{BC} \left(\frac{0.189}{SOC} + R_i \right) \quad (15)$$

$$R_i = 0.15[1 - 0.02(T_c - T_r)] \quad (16)$$

3. Energy Management of Proposed PVBDS

To achieve optimal performance of the proposed PVBDS, it is required to maximize the use of renewable energy, minimize diesel consumption, and maximize battery usage. Figure 2 gives the block diagram of the proposed energy management (EM) subsystem. EM subsystem has two main functions; energy control and monitoring the system performance. Control unit; PV power generation is the primary energy source, the battery as the supplement, and the diesel generator power as the backup source of energy. An operational control strategy suggested in this work consists of several set points, which are to switch on the diesel or OFF solar radiation, battery state of charge, and load demand. The flowchart of the proposed control strategy is given in Fig. 3. The meteorological variables (the solar irradiance and the ambient temperature) are obtained, and hourly load demand is calculated. Based on energy balance; the PV generated power (P_{PV}) is compared to load power (P_L). The extra energy should be released if P_{PV} is larger than the needed load power and the battery is fully charged.

The battery is charging from surplus energy if the state of charge (SOC) is less than 100 %. However, if the P_{PV} is less than P_L and the depth of discharge (DOD) is less than 80%, the battery will discharge and meet the load requirements. Meanwhile, if DOD is greater than 80%, the diesel generator (DG) should be turned on to make up for the energy shortfall. If P_{DG} is less than P_L , then there will be

deficit energy while if P_{DG} is greater than the P_L , the excess energy is used to charge the battery.

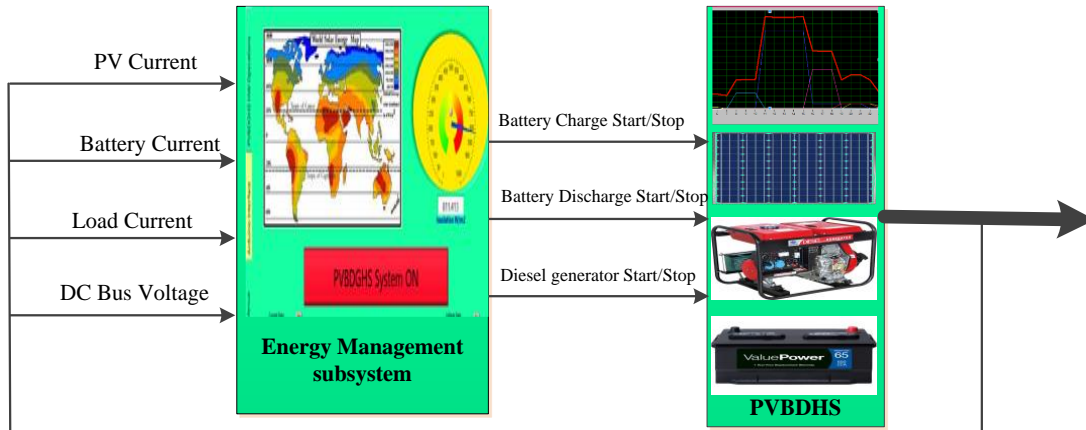


Figure 2. Block diagram of the proposed energy management subsystem.

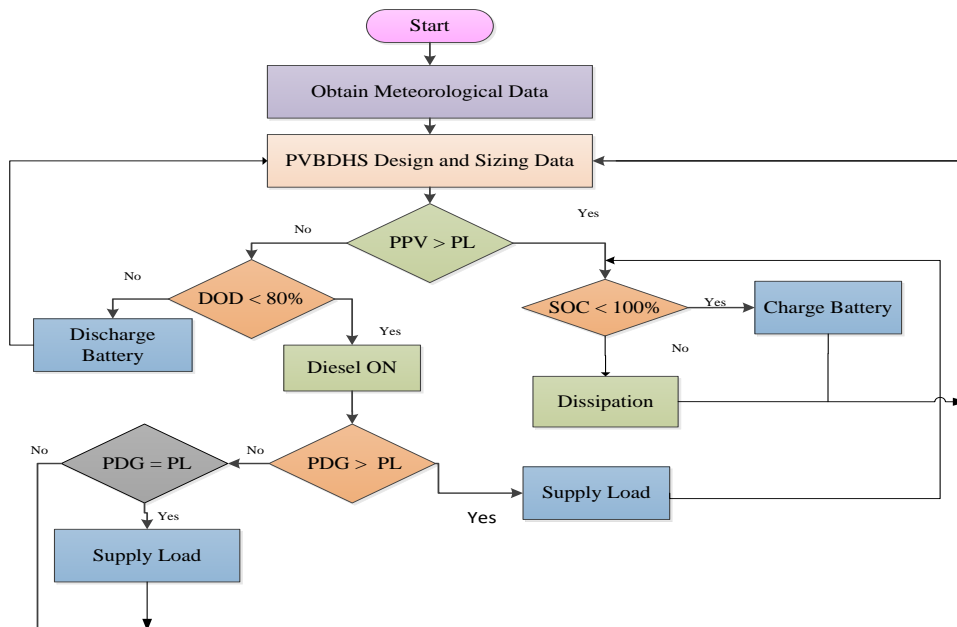


Figure 3. Flowchart of control strategy of PVBDS system.

With the complexity of the system and installation in remote areas, the necessity of an automated monitoring and control system is very vital. The operator should have the ability to connect to the system and enter corrective commands to avoid fault conditions such as the change between different operating cases. In addition, the operator should monitor and analyze system operation parameters, which are PV current, battery current, load current, diesel status, and system voltage to automatically adjust and optimize the energy management of the system. The

simulation based on LabVIEW is carried out before system implementation. Customized LabVIEW system is suitable for monitoring PV systems under different environmental conditions variation. This system includes two parts software and hardware. The collected data are processed using LabVIEW to enable communication with the Arduino board for serial bus setup, output string-processing, and conversion of the transmitted data to a binary value. Different operating modes of the proposed PVBDS system depend on load type and solar radiation values have shown in Table 1.

Table 1. The operation modes of the proposed PVDHS.

Time	Load Type	Operation cases	Condition	Diesel status	Battery status
Day hours	Semi Dynamic	Case 1	$P_L > P_{PV}$ SOC<100%	ON	Charge
	Dynamic	Case 2	$P_L > P_{PV}$ 30%<SOC<100%	ON	Discharge
	Shallow	Case 3	$P_L < P_{PV}$ SOC<100%	OFF	Charge
Night hours	Dynamic	Case 4	$P_{PV} = 0$ SOC<100%	ON	Charge
	Shallow	Case 5	$P_{PV} = 0$ 30%<SOC<100%	OFF	Discharge

4. Results and Discussion

The suggested PVBDHS is used to power a farm with a maximum load requirement of 3.5 kW. Figure 4 depicts the load profile's hourly variation. The load profile is divided into two parts dynamic load with a peak power of 3.5 kW and a shallow load with a peak power of 2.2 kW. The subprogram is built in the LabVIEW GUI to calculate the daily average global solar irradiance on horizontal and tilted surfaces at the site under consideration. Real-time solar radiation and temperature values are measured online using internet-based NASA from LabVIEW weather station. Cairo city located at 29.77° of latitude and 30° of longitude obtained according to NASA data [52], the yearly average solar radiation is 5.01 kWh/m² /day is taken into account as a site under consideration. There are numerous parameters required to calculate the horizontal and tilted solar radiations during running the program. The operator can change different parameters in the control panel of solar irradiance at any location, time, tilted and azimuth angles. Figure 5 shows the page of the GUI front panel. It contains all buttons required for launching the other pages of GUI. In addition, the page contains the toggle switch between emulation mode and hardware mode. Moreover, it contains the knob of solar radiation control and the buffers of reading data from data acquisition boards. Finally, the serial interface parameters; baud rate, com port, stop bit are presented.

The Block diagram of virtual instruments developed in LabVIEW to monitor data of PVBDHS system is shown in Fig. 6. It contains the initialization and configuration blocks of the serial communication between LabVIEW and Arduino UNO by defining the type of used Arduino, type of serial communication (USB), and baud rate. Also, contain an analog to digital converter (ADC) block diagram, solar

radiation block diagram, sizing block diagram, and control block diagram.

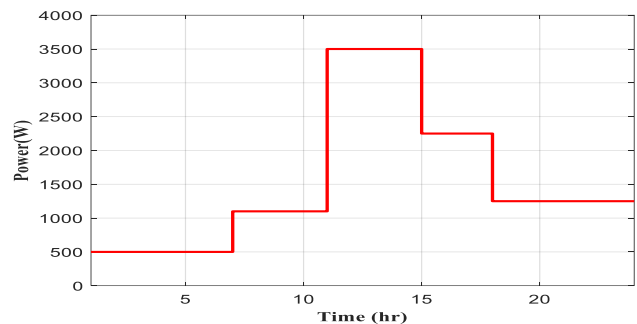


Figure 4. Load profile variation over the day.

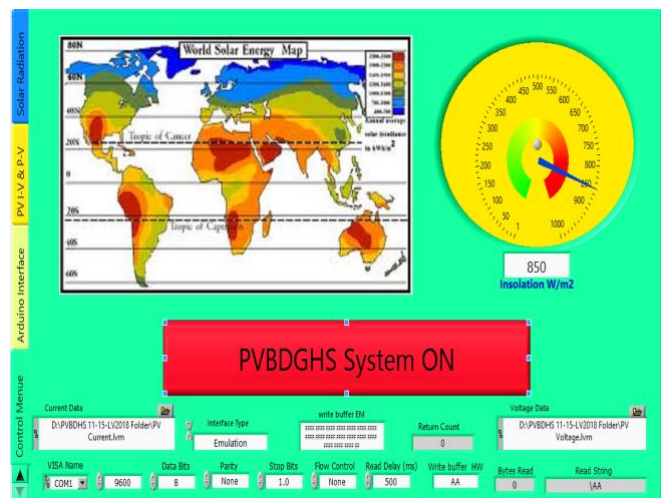
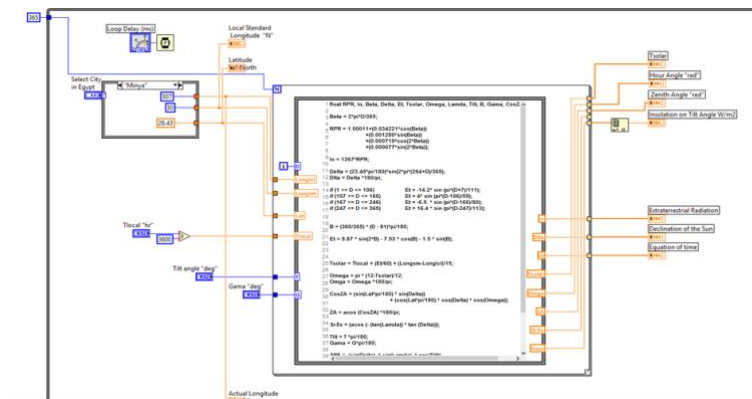
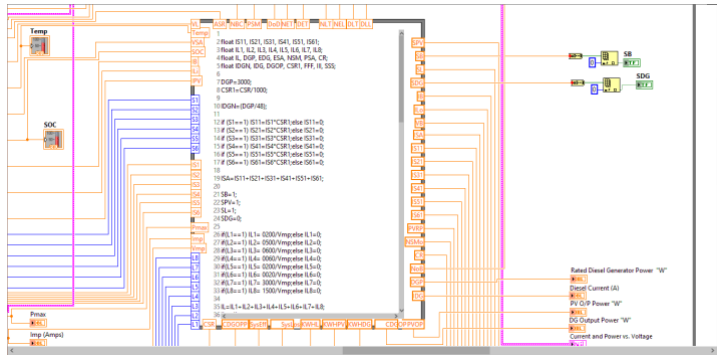


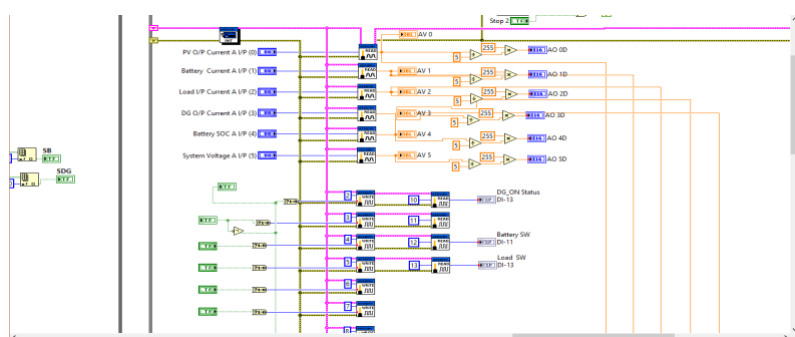
Figure 5. The main control page front panel.



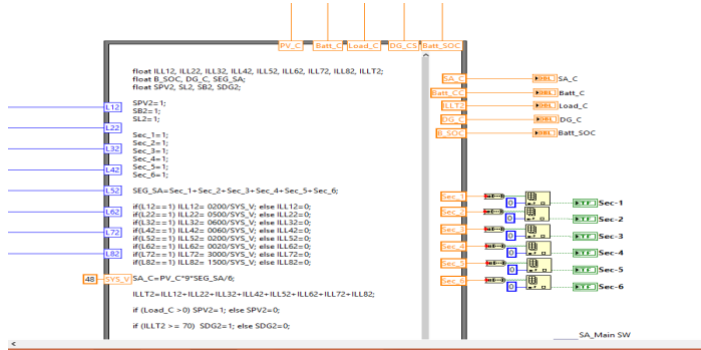
(a)



(b)



(c)



(d)

Figure 6. Block diagram of virtual instruments of PVBDS system. a) Solar radiation block diagram, (b) Sizing block diagram, (c) ADC block diagram (d) Control block diagram.

4.1. PVBDHS Sizing Results

A sizing sub-program is built using LabVIEW GUI. The sizing window is shown in Fig. 7. The input parameters are load data (average load at daylight time and night time), PV module and batteries specifications (solar module power, battery ampere-hour capacity, average yearly solar radiation), and balance of system efficiencies. The PV power, number of solar modules, number of storage batteries at 48 V, rated diesel generator power are 2.16 kW, 12 PV modules (each of 180 W), 16 batteries (each of 100 Ah), and 2 kW DG are the obtained sizing output parameters respectively. In this window, the operator can change the PV and batteries specifications, which results in changing the sizing results. I-V and P-V characteristics of PV array based on sizing results are shown in Fig. 8. The optimal sizing of the PVBDHS is a major factor that affects the viability of the implemented control strategy.

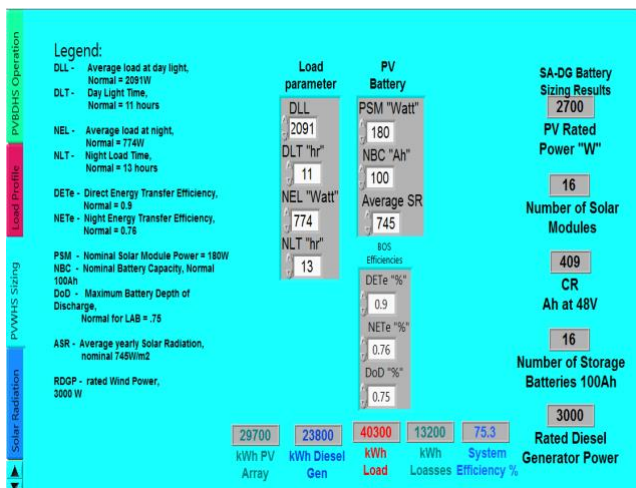


Figure 7. PVBDHS sizing parameters and results menu.

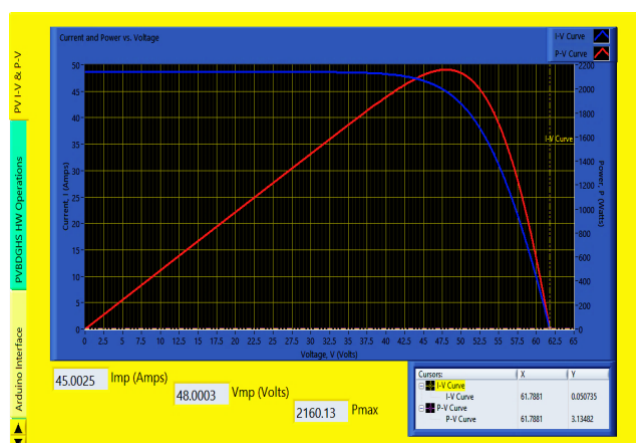


Figure 8. PV array I-V and P-V characteristics results.

4.2. PVBDHS Monitoring Results

Figures 9-13 depict the Front Panel of several PVBDHS monitoring scenarios. The figures show the PVBDHS wiring diagram, the number of PV strings, load branches, and

control switches in emulation mode. As input parameters change, the instantaneous results of system variables alter dynamically. In addition, the hybrid system's output power and battery status are displayed on the GUI monitoring page, as well as discharging and charging. As shown in the diagrams, as load demands change, the EM subsystem can alter battery status based on SOC value and diesel status consecutively. The different cases of system operation are tested and the EM subsystem proves its ability and accuracy in monitoring and control of PVBDHS performance.

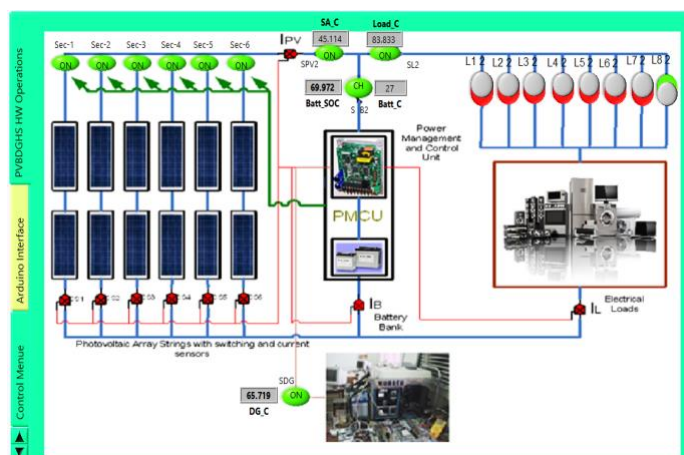


Figure 9. Semi Dynamic mode (Case 1) PV supply Load, Diesel On, and Battery charge.

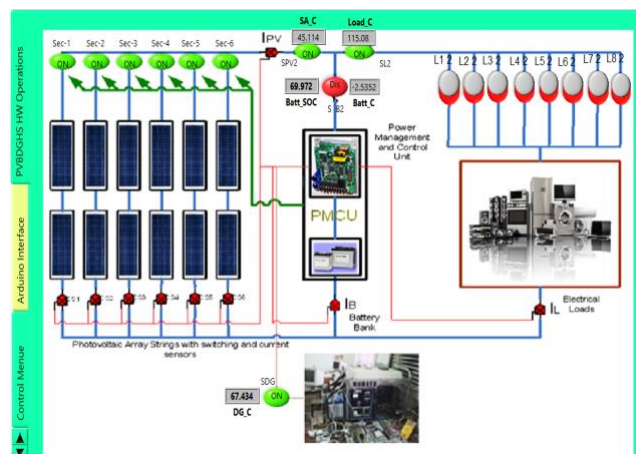


Figure 10. Dynamic load day mode (Case 2) All loads are connected PV supply loads, Diesel-ON, and Battery discharge.

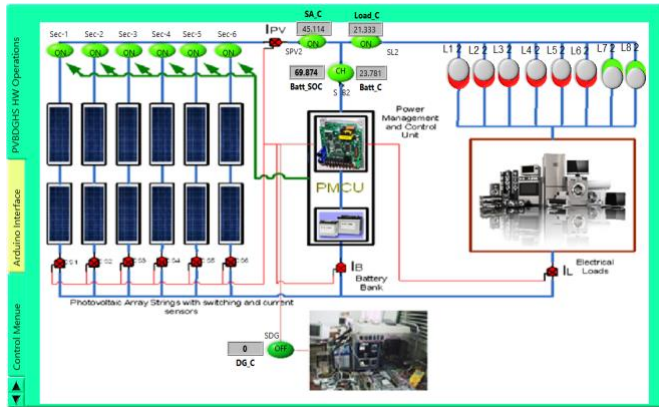


Figure 11. Shallow load day mode (Case 3) PV supply load, Diesel-OFF, and Battery charge.

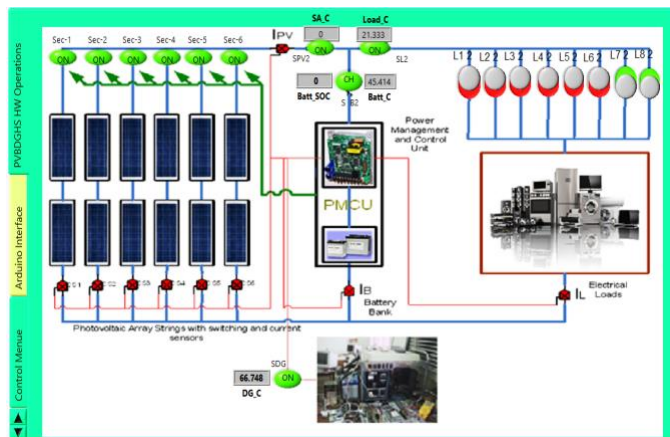


Figure 12. Dynamic load (Case 4), night mode, PV have zero output, Diesel ON, and Battery charge.

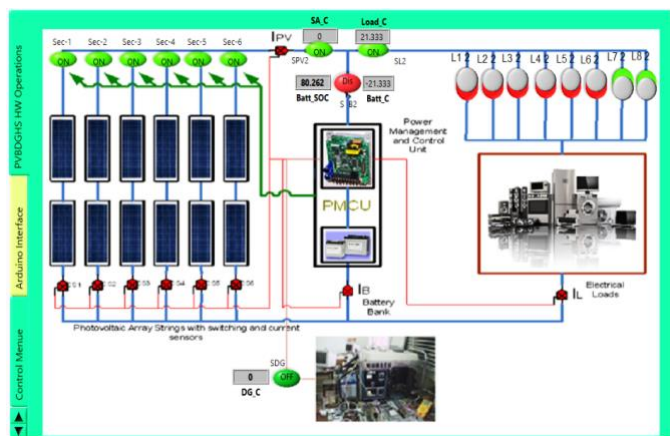


Figure 13. Shallow load night mode (Case 5) PV has zero output, Diesel-OFF, and battery discharge.

4.3. Feasibility Analysis

The Front Panel of the LabVIEW monitoring windows with Arduino for different cases of prototype operation tests are carried out as given by Figs. 14-17. The mode of

operation is determined by the load current and PV current. The battery's status is determined by the battery current signal, which is negative while the battery is being discharged and positive when it is being charged. The following are the test scenarios: initially, the load is turned off, and the PV arrays are connected and charging the batteries. As PV arrays generate power, the batteries start charging, and their current increases.

In Fig. 15; the PV power is sufficient to supply the load and to charge the batteries. The load is connected and the PV arrays start to charge batteries and feed load at the same time with their required power for operation. Figure 16 shows the load current is larger than PV generated current, so the batteries start to discharge to feed load with the required power needed for operation. The negative values represent that batteries are in discharging mode.

The EM pages show that the load is completely fed from the battery during night hours, as PV current is equal to zero as given in Fig. 17.

Figure 18 shows the variation of power generated by PV, load power, and diesel generated power with time over the day. PV supply load with the required power during day hours while diesel generator supply load during night hours and in case of dynamic load start in operation during day hours.

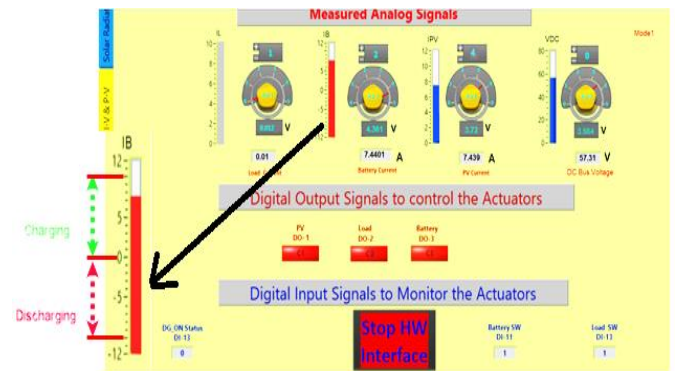


Figure 14. Case 1; PV voltage, and current.

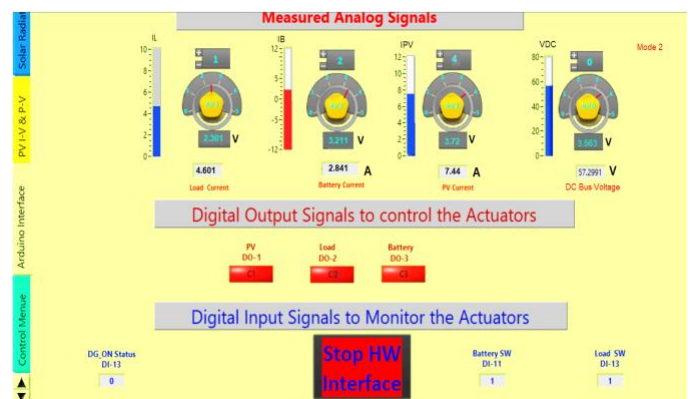


Figure 15. Case 2; PV, Load, and batteries current.

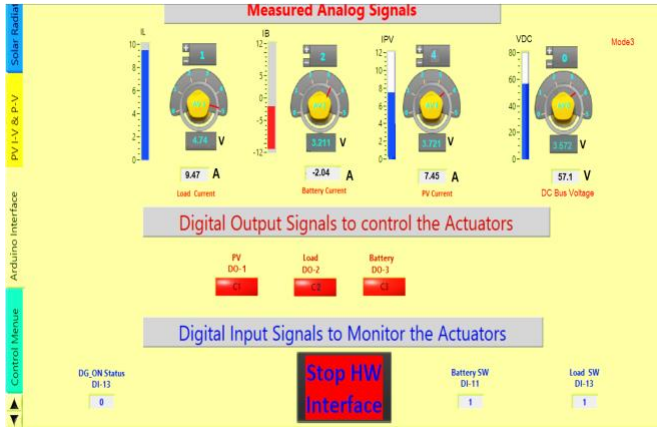


Figure 16. Case 3: PV, Load, and batteries current.

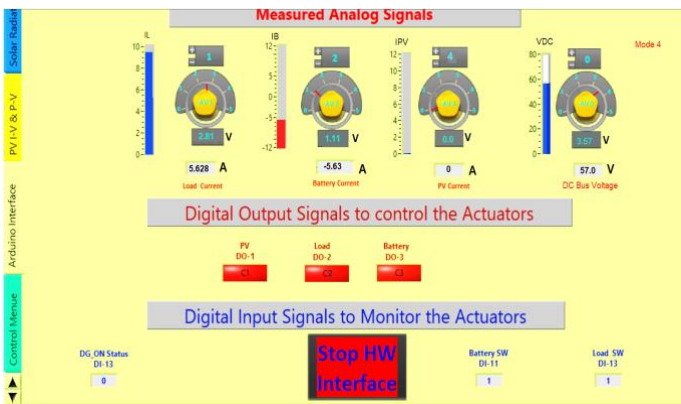


Figure 17. Case 4; PV ON, battery status changing when load power changing.

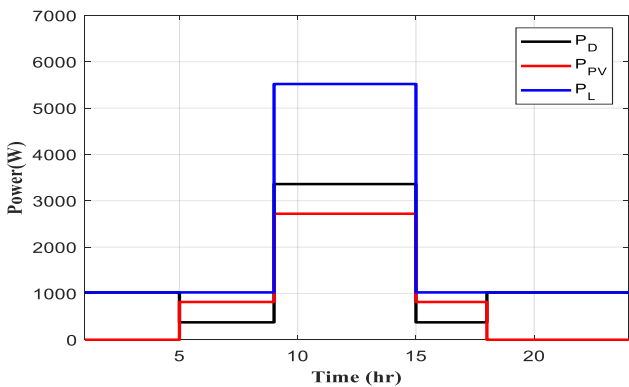


Figure 18. PV, diesel, and load power variation over the day.

Another case for testing management unit; study the constant load over the day with the power generated by PV array and diesel generator and stored in batteries is presented in Fig. 19. The PV arrays supply load and charge the batteries during the day hours however the diesel generator and batteries supply the load during night hours. In the final case; the system operates at dynamic load over the day as given in Fig. 20. The diesel generates power and supplies the load over the night hours and during day hours the PV array

generates power which aids the diesel generator to feed the system with the required power.

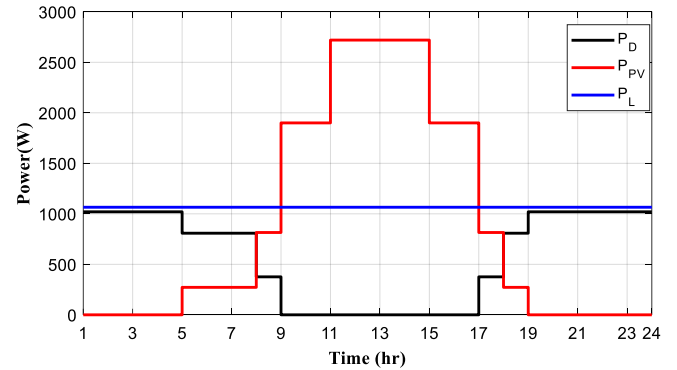


Figure 19. PV and diesel generated power variation with constant load over the day.

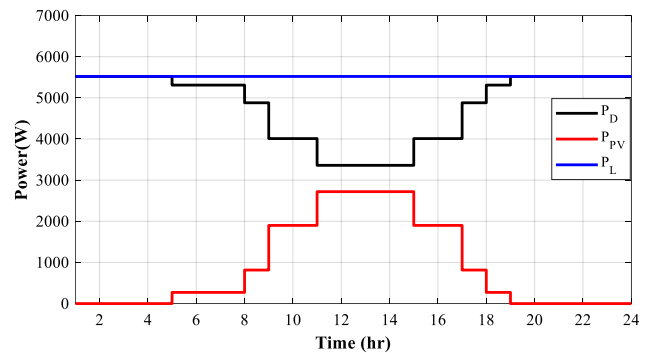


Figure 20. PV and diesel generated power variation with dynamic load over the day.

4.4. Experimental setup

The applied system consists of twenty-four PV modules connected in six strings in parallel; each string has four modules in series. The six strings are connected through contactors. Four batteries are connected in series, DC-bus voltage is 48 V, and finally, diesel generator. Table 2 shows the specification of the different components used in the system setup. Arduino Uno is used for interfacing between the EM subsystem on the laptop and the power system. The system performance is monitored and controlled through a control unit that employs an Arduino microcontroller connected to a PC in addition to several transducers and signal conditioning devices to the EM subsystem using a specially built LabVIEW software program. To switch between different cases a relay switching system is implemented. The developed control panel includes three transducers to measure the currents of PV, batteries, and load. PV current and battery state of charge are monitored, displayed, and recorded. The control scheme was calibrated for different: PV current, battery current, and load current at different irradiation and load values. The experimental setup has been built in the ERI /photovoltaic laboratory to validate the correct operation of PVDBHS. The complete experimental setup is shown in Fig. 21.

Table 2. PVDHS components specifications.

Components	Specification	
PV module	Current	4.4 A
	Voltage	17 V
	Power	75 W
Batteries	Voltage	12 V
	Rate capacity	100 Ah
Diesel generator	Rated power	3 kW

4.5. Experimental results

The system prototype is interconnected together to test and validate the system performance as given by Fig. 22. The screen of the monitoring page is divided into three categories, which are analog input signals, digital outputs for actuators, and digital inputs for actuators.



Figure 21. Experimental system setup.

On the scope, Figure 23 depicts the current variation of the PV array, load, and batteries. As the load current rises, the batteries begin to discharge in order to provide the load with the necessary power from the PV array. When the load current is low, the batteries begin to charge, allowing the excess energy generated by the PV array to be stored.

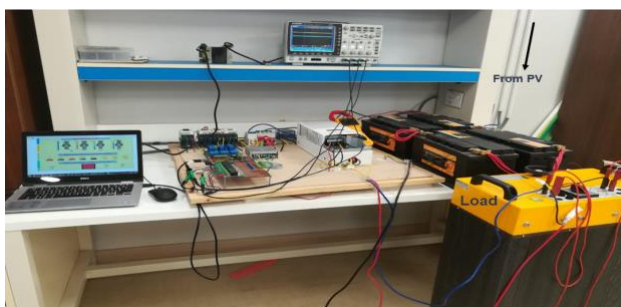


Figure 22. Prototype of PVDHS testing.



Figure 23. Case 4; PV ON, battery status changing when load power changing.

5. Conclusion

The PV battery diesel hybrid system (PVDHS) system performance was controlled and monitored using a LabVIEW-based energy management subsystem in this work. Photovoltaic panels and a diesel generator with a battery storage bank are included in the proposed hybrid system, which can supply 3.5 kW as a maximum load requirement. First, the mathematical model of the PVDHS system's various components and the energy management subsystem were provided. The design and the identification of the PVDHS system components have been made. Then the energy management of the hybrid system was introduced by using the LabVIEW program. Interfacing between LabVIEW and Arduino microcontroller was carried out. The PVDHS system's results in various operation modes were investigated. The high precision of the suggested control and power management unit was used in various scenarios of system operation at various times throughout the day. Finally, the implemented PVDHS pilot plant can be used in remote areas where electric utilities cannot be reached. From the above discussion for experimental prototype results, the design is successfully tested using an experimental setup. Finally, remote monitoring of PVDHS based LabVIEW program was used to display the data collected.

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