Journal of Agriculture Science & Technology ISSN 1561-7645 JAGST 20 (3) 2021, 4-15
https://ojs.jkuat.ac.ke/index.php/JAGST/index (15th JKUAT Conference – Special Issue)

ORIGINAL RESEARCH ARTICLE

Modelling and Energy Management Strategy in a Grid Connected Solar PV-battery Energy Storage System

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ABSTRACT

Currently, the world is experiencing fast growth in electricity demand for both its domestic and industrial use. The use of green energy as an alternative to the generation of electricity by fossil fuel is currently on the rise. The energy produced from renewable sources is intermittent and this poses a challenge combining it with the electrical power grid. Because of the unreliability of renewable energy sources, a complementary source like a battery storage system is provided to solve the intermittency problem.

This study aims to model and perform Energy Management on a grid-connected solar PV-battery energy storage system. The management system is expected to use the energy obtained from renewable sources and the grid efficiently and reduce the grid electricity need. The solar PV supplies power to the load when sunlight is sufficient and charges the battery when its power exceeds the load demand. The battery storage system supplies the load when solar PV is unable to produce enough power to serve the load. The grid intervenes and supplies the load when the battery power drops below the load demand. MATLAB Simulink software is used for modelling and simulation because of its effectiveness. The Arduino-based microcontroller is chosen to perform real-time energy management because of its effectiveness in switching actions and flexibility of expansion. One Sun Earth Solar Power 90 W solar panel, 150 AH lead-acid battery and 60 W incandescent lamp are the main Micro-grid components in this study. Raspberry Pi is introduced (new to related literature about PV) to forecast the next day solar PV power production. Simulation results show that the load was served at all times by either the micro sources or the grid. The system model is based on weather conditions and load demand of the study area. The system is economical because it reduces the grid electricity need, prolongs the battery life, next day PV power production is predictable and consequently the system caters for possible grid failure.

Keywords: Energy Management System, Energy Storage System, Micro-grid, Solar Photovoltaic.

1.0 INTRODUCTION

The energy from conventional sources are not naturally renewable. In addition, using such sources affect the environment. Combustion of fossil fuel in the process of electricity generation causes the emission of harmful gases to the atmosphere like sulfur dioxide and nitrogen dioxide which affects the ozone layer. The researcher's effort is geared towards cleaner energy production. The use of green energy as an alternative to the generation of electricity by fossil fuel is currently on the rise. Technological innovation, government policies and the drive to address climate change have made renewable energy gain global popularity (Polanco, et al., 2018). Authors in (Sedighizadeh, 2018) defined a Micro-grid as a low tension distribution network consisting of distributed generations, storage devices and loads that are flexible. A Micro-grid system is a technology that provides a solution to green energy production (Chowdhury & Boruah, 2015). The Micro-grid system is controllable, provides reliable energy, is localized, minimizes environmental pollution and can reduce grid electricity needs (Li, 2015). The commonly installed distributed generations are solar photovoltaic (PV) and wind turbine systems. Solar energy depends on changing weather conditions i.e. irradiance and temperature. Due to this intermittence nature of solar energy, it can serve the load only when solar radiation is sufficient or when the sky is clear and the sun is out. This is a disadvantage in the use of solar PV and poses the biggest challenge of combining it with the electrical power grid. Batteries are therefore used to store surplus energy generated from PV panels and later on release this energy when the necessary environmental parameters of irradiance and temperature drop in their value. This reduces the disadvantage of the unreliability problem of solar energy. Over some time, several studies have been conducted on Modelling and Energy Management in Micro-grid. The researchers have used different perspectives to conduct such studies. Authors in (Baams, et al., 2017) used deep-cycle lead-acid batteries to model energy storage systems for their 3.4 MW grid-connected PV-battery hybrid system for Adamawa State and addressed synchronization issues. The study did not address energy management between the grid and the micro sources. The study conducted by (Dash & kumri, 2018) modelled and simulated a 400 kW grid-connected solar PV but did not use an energy storage system. Energy management between the micro source and the utility grid was not performed in this study. Authors in (Moncecchi, et al., 2020) used a Li-ion battery as a technology for modelling a PV-based Micro-grid. Authors in (Liu, et al., 2017) modelled and simulated a community Micro-grid system under MATLAB environment to manage PV and battery energy storage facilities. Monitoring the health status of PV parameters was not covered in this study. The health status of PV modules influences the total energy production. Authors in (Chowdhury & Boruah, 2015) modelled and simulated a Micro-grid system that can be operated in both islanding and as well as in grid-connected mode. The research was to allow for a full understanding of the behavior of Micro-grid.

Efficient energy use is important for the study of Micro-grid. Effective Energy Management System (EMS) may result in providing uninterruptible power supply to the consumer, decreasing grid electricity needs or minimizing operational cost by reducing fuel consumption and minimizing environmental pollution. Authors in (Kelly, 2016) concluded that the main goal of energy management is profit maximization and minimization of operational costs without affecting the production and quality of the product. The environmental effect resulting from this goal is minimized. The quantity of energy used can be reduced by downsizing, use of more efficient equipment and by substituting the energy form.

Various Energy Management techniques have been studied in the literature namely; Evolutionary Algorithm and Neural Network in (Wang & Shen, 2019), Internet of Things based Solar Energy monitoring system in (Tellawar & Chamat, 2019), Firefly Algorithm in (Sufyan, et al., 2019), Arduino-based Microcontroller in (Özer, et al., 2017) and many others. Authors in (Nagalakshmi, et al., 2017) applied an Energy Management System to control the power flow in the Micro-grid by adjusting the power imported from the grid, the renewable generations and the loads to meet the operational objectives. Authors in (Shayeghi, et al., 2019) provided a detailed literature review on the Micro Grid EMSs by classifying them into various categories. Authors in (Tabaa, et al., 2019) used MATLAB/Simulink software to perform Energy Management System in a grid-connected PV-battery system. Authors in (Özer, et al., 2017) used Arduino AT mega 328 to perform EMS in a power system consisting of various renewable energy sources. The efficiency of energy generating sources were improved. In (Nagalakshmi, et al., 2017) Arduino was used to design and implement an EMS in a home using renewable energy from various sources to reduce energy consumption rate. Emissions of carbon dioxide to the atmosphere was also reduced. Authors in (Putra, et al., 2017) used Raspberry Pi and Arduino Nano to monitor energy and power flow in a PV Power Plant. Monitored values are shown in real-time. Authors in (Revathi, et al., 2017) used Raspberry Pi to monitor the health status of photovoltaic panels remotely. A weather monitoring model based on Raspberry Pi was developed by authors in (Rasal & Rana, 2016). Wind direction, temperature, rainfall and humidity were recorded and displayed in this model.

The main aim of this study is to model a grid-connected solar PV-battery energy storage system and apply an energy management algorithm to manage its energy sources in a real-time application, monitor the PV parameters and estimate next-day energy production from the solar PV. The management system is expected to use the energy obtained from renewable sources and the grid efficiently, prolong the life of the battery energy storage system and reduce the grid electricity need. Modelling of components and Energy Management Systems in Micro-grid have been studied mostly by simulations. Real-time studies are rare. This paper implements the modelling of components by simulation using MATLAB Simulink software because of its effectiveness. Real-time Energy Management using Arduino microcontroller is proposed. In (trademark@arduino.cc., 2018), Arduino software is easy to use, the software can be extended by advanced programming, Arduino boards are less expensive, the preassembled Arduino module costs less and has extensible hardware. Arduino Nano is an AT mega 328p-based microcontroller small in size than the Arduino Uno (theengineeringprojects.com, 2018). Raspberry Pi which is new to related literature about PV is introduced in this study to forecast the next day solar PV power production.

2.0 MATERIALS AND METHODS

2.1 Micro-grid Modeling

Micro-grid components were modeled using MATLAB/Simulink software, the most used software by many engineers and researchers because of its effectiveness. Mathematical modeling equations are used in this modeling.

2.1.1 PV Modelling

Electrical modelling of a PV system can be in the form of a single diode model or double diode model with a series resistor or both series and parallel resistors. Most research have been conducted on a single diode model as in (Baams, et al., 2017), (Tabaa, et al., 2019), (Chakir, et al., 2019) and (Bellia, et al., 2014). This study models the PV system based on the single diode model of Fig. 1; the equivalent circuit having both series and shunt resistors.

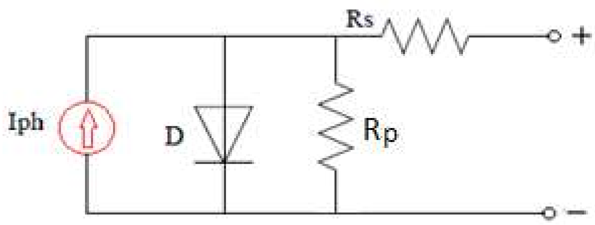

Figure 1. Single diode model with series and shunt resistors

The solar cell output current at standard test condition as in (Chippada & Reddy, 2020) is found by applying equation (1).

$$I = I_{ph} - I_o\left[\exp\left(\frac{V + IR_s}{AV_t}\right) - 1\right] - \left(\frac{V + IR_s}{R_p}\right) \quad (1)$$

Where I is the solar cell output current, I_{ph} is the photocurrent, I_o is the diode reverse saturation current, V is the diode voltage, R_s and R_p are the equivalent series and parallel resistors

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respectively, A is the ideality factor of the diode generally taken between [1-3] and V_t is the thermal voltage. The Simulink model of a solar PV module with input parameters is shown in Fig.2. Sun Earth Solar Power 90 W solar panel was chosen for this simulation. The open-circuit voltage of the solar panel ranges from 0 to 22.3 V.

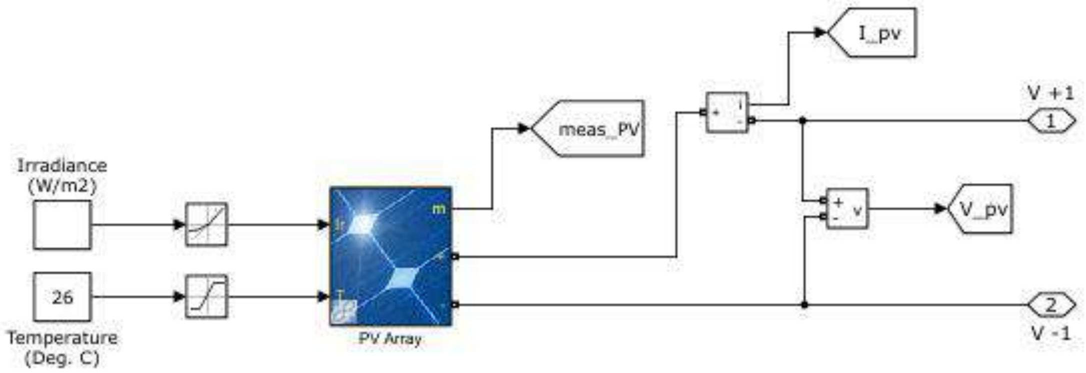

Figure 2. Simulink model of a solar PV

2.1.2 DC-DC Converter Modelling

In a photovoltaic power generation system, boost converters are preferred because of their ability to step up the module voltage to higher values. The converter average output voltage as in (Sharma, et al., 2018) is given by equation (2).

$$V_O = I_L R_L \qquad (2)$$

V_O is the output voltage, I_L is the load current and R_L is the load resistance. The boost converter and associated control switches are modelled in the Matlab-Simulink environment as shown in Fig. 3.

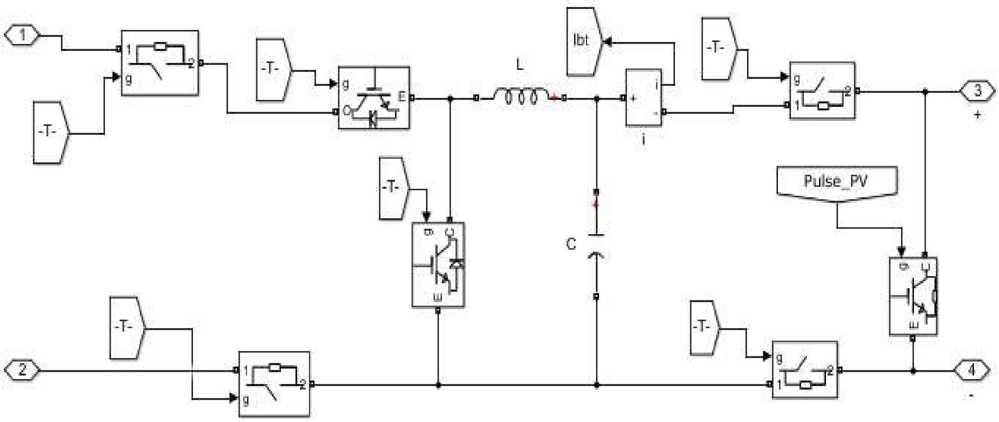

Figure 3. Simulink model of a DC-DC Converter

2.1.3 Inverter Modelling

Voltage, phase and frequency are harmonized to the grid. This model uses a single-phase IGBT bridge as its converter to operate as unidirectional from the PV panel and the battery to the A.C load. The Simulink model of an inverter is shown in Fig. 4.

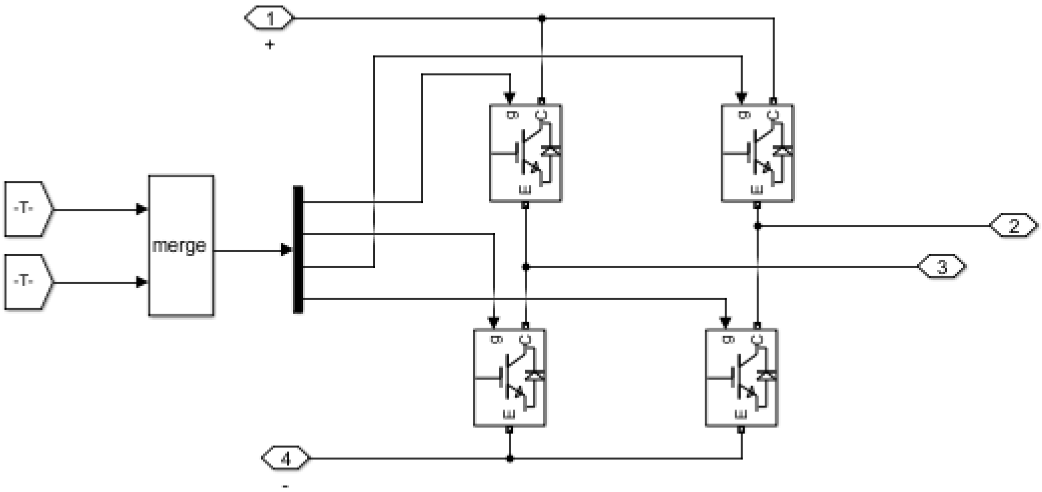

Figure 4. Simulink model of an Inverter

2.1.4 Energy Storage System Modelling

A Lead-Acid battery generic model was used in this modelling. The battery is low cost and readily available. In (Mora & Amaya, 2018), the current battery voltage is found by applying equation 3 for charging (+) and discharging (-) states.

$$V = V_{OC} \pm IR \qquad (3)$$

Where V is the current battery voltage, V_{OC} is the open-circuit voltage of the battery, I is the battery charging current from an external charge which is approximately zero in idle state and R is the internal resistance of the battery. The battery state of charge is found by applying equation (4).

$$SOC = \frac{Q - Q_{disc}}{C_{bat}} \qquad (4)$$

Where SOC is the battery state of charge, Q is is the actual battery charge, Q_{disc} is the actual battery discharge rate and C_{bat} is the battery capacity. A 150 AH Lead-Acid battery was used in this study. The Simulink model of a Lead-Acid battery is shown in Fig. 5.

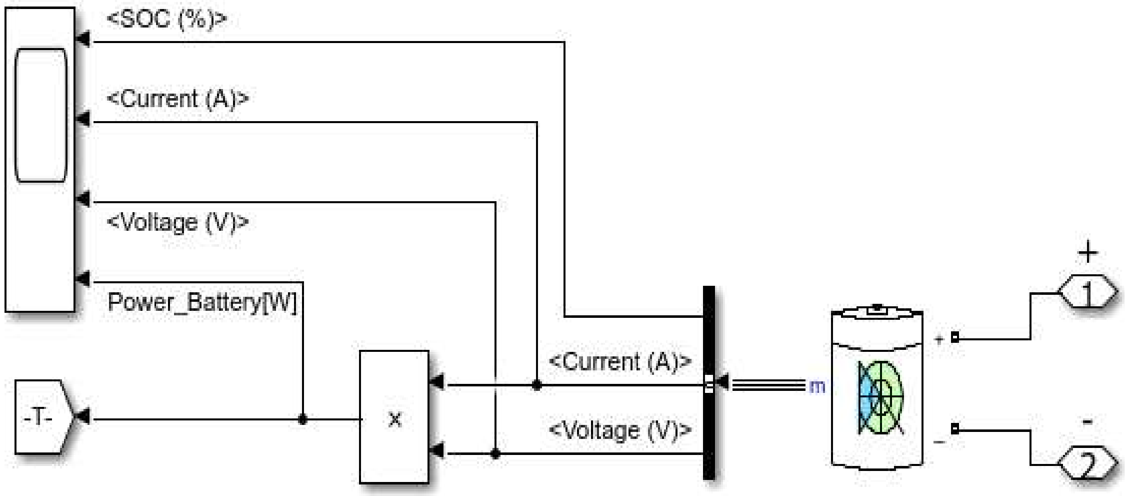

Figure 5. Simulink model of a Lead-Acid battery

2.1.5 Load Modelling

The load is modelled as a resistor-inductor-capacitor series circuit. The Simulink model of the load and associated switching circuits is shown in Fig. 6. The load has a nominal voltage of 240 V rms, nominal frequency of 50 Hz, the active power of 60 W and a load type of constant z.

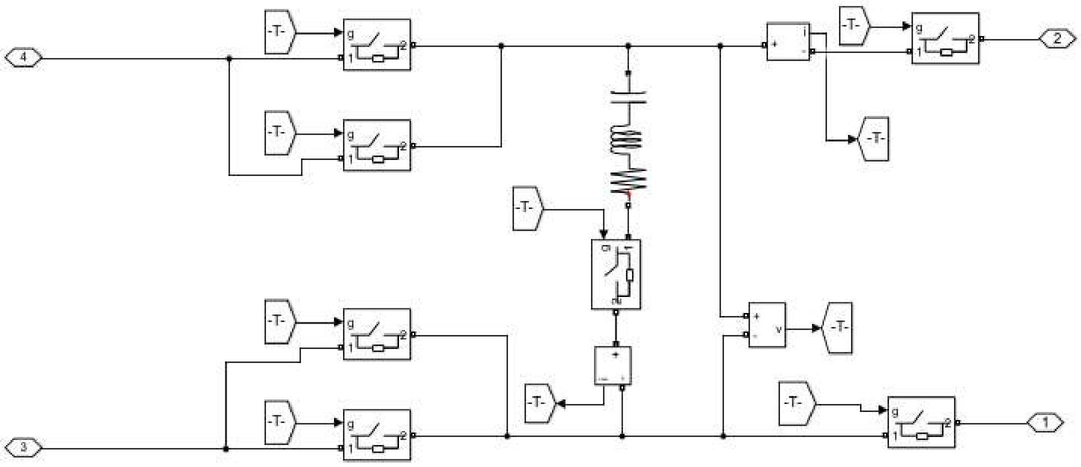

Figure 6. Simulink model of electrical load

2.1.6 Grid Modelling

The power grid is modelled as a single-phase 240 V a.c source supplied from a typical 6.6 kV distribution feeder. The Simulink model of a power grid is shown in Fig. 7.

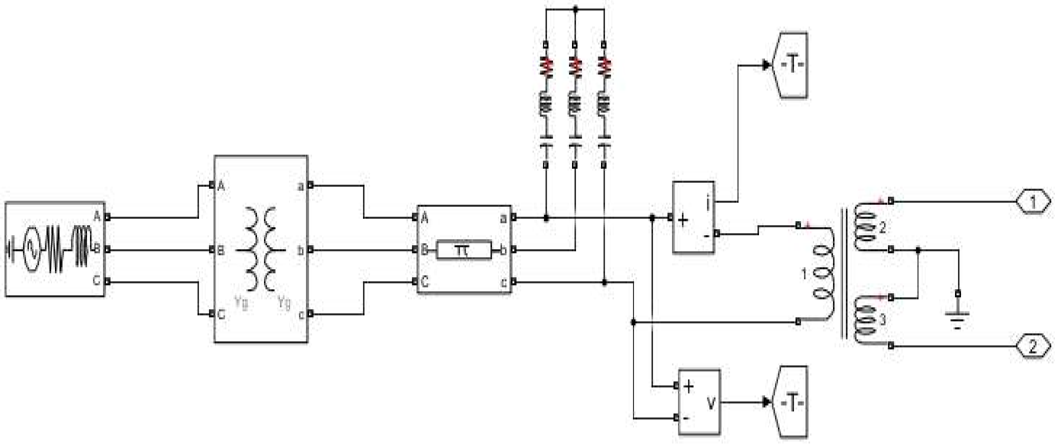

Figure 7. Simulink model of a power grid

2.1.7 The Complete Model of the Micro-grid System

The complete Simulink model of a grid-connected solar PV-battery energy storage system is shown in Fig. 8. The controls and scopes are modelled too to enable energy management and surveillance of the Micro Grid system.

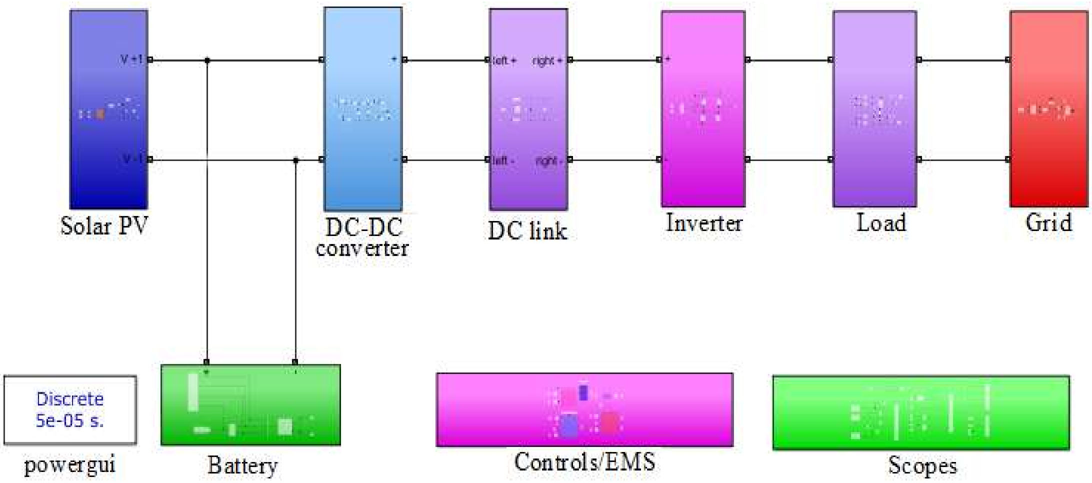

Figure 8. Simulink model of the Micro-grid system

2.2 Energy Management Scenario

The Energy Management Scenario studied is such that when sunlight is sufficient (with sufficient solar irradiation), the solar PV supplies power to the load provided the load demand is met. When the solar power exceeds the load demand, the excess charges the battery. The battery storage system supplies the load when the solar irradiation is insufficient to generate enough power from the solar panel to serve the load. The battery supplies power to the load provided the load demand is met. The grid intervenes and supplies the load when the battery power drops below the load demand. The main sub-systems used to achieve the proposed energy management strategy were the PV controller, the inverter controller, the battery controller and the MPPT controller. The Simulink model of the energy management system with associated inputs and outputs is shown in Fig. 9.

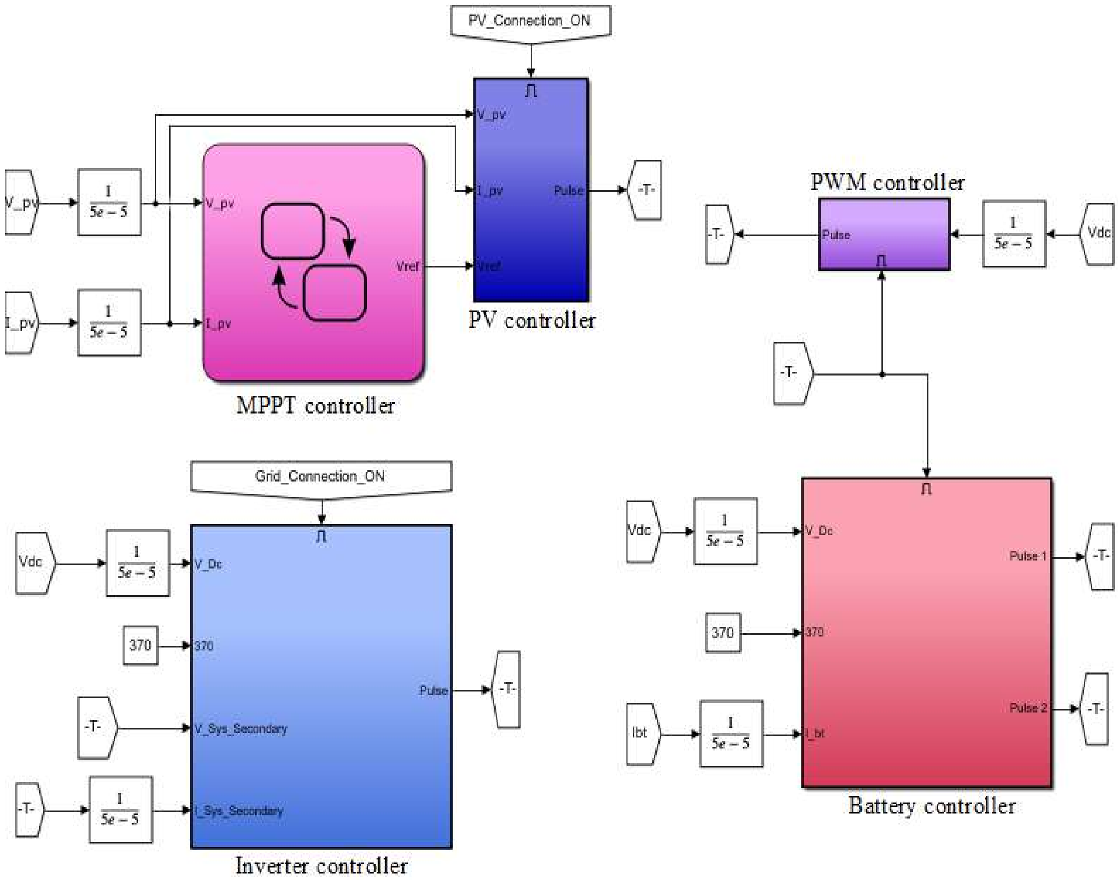

Figure 9. Simulink model of energy management controls

The input to the PV controller are PV output voltage Vpv, PV output current Ipv and a reference voltage V_{ref}. The PV controller houses the PID controller which implements discrete-time control algorithms having advanced features like external reset, anti-windup and signal tracking. It sets the PV-load connection to ON when there is sufficient solar radiation and to OFF when power from the PV is not sufficient to meet the load demand. The battery controller senses the D.C voltage from the DC-link and the current drawn from the battery. It also has advanced features like external reset, anti-windup and signal tracking able to disconnect the battery from over-discharge and reconnect the battery on charging. The inverter controller takes in the D.C voltage signal from the D.C-link, grid voltage signal and grid current signal. It sets the grid-load connection to ON when power from the micro sources are not able to meet the load demand. It sets the grid-load connection to OFF when the power from the micro sources is sufficient to meet the load demand. It houses Phase Locked Loop (PLL) system used to synchronize on a variable frequency sinusoidal signal. The MPPT controller sweeps through the panel voltage to find the best combination of voltage and current to produce the maximum power. It continuously tracks and adjusts the voltage to generate the most power even if the weather is not favorable.

2.3 Energy Saving Estimate

In (de Lara, et al., 2019), the solar energy production within a time frame of a single day can be estimated using equation (5).

$$E = Ppv * G * R \qquad (5)$$

Where E is the daily energy generated, Ppv is the PV power, G is the solar irradiation per day and R is the system performance ratio or efficiency taken as 80%.

The economic aspect of installing the PV system to supplement the grid electricity need was conducted. After obtaining the total installation cost of the PV system, the daily energy generation from the PV system was calculated using equation (5). The calculation of total financial savings was done. The total financial savings, which factored in the payback period of the PV installation system, was arrived at by subtracting the daily energy generated from the PV system from the total power consumed by the load for a period of three months (the expected period is the life expectancy of the solar system installed). The difference was multiplied by the current National Electrical Energy Agency tariff to get the financial estimate or saving for the three months studied.

3.0 SIMULATION RESULTS

The complete model of Fig. 8 was simulated in MATLAB/Simulink software with the powergui simulation type set to discrete. The model was simulated at 600 W/m2 irradiance and a temperature of 26°C. The simulation results of load, battery and grid switching are shown in Fig 10. PV voltage, PV current and DC-DC converter output voltage are shown in Fig. 11.

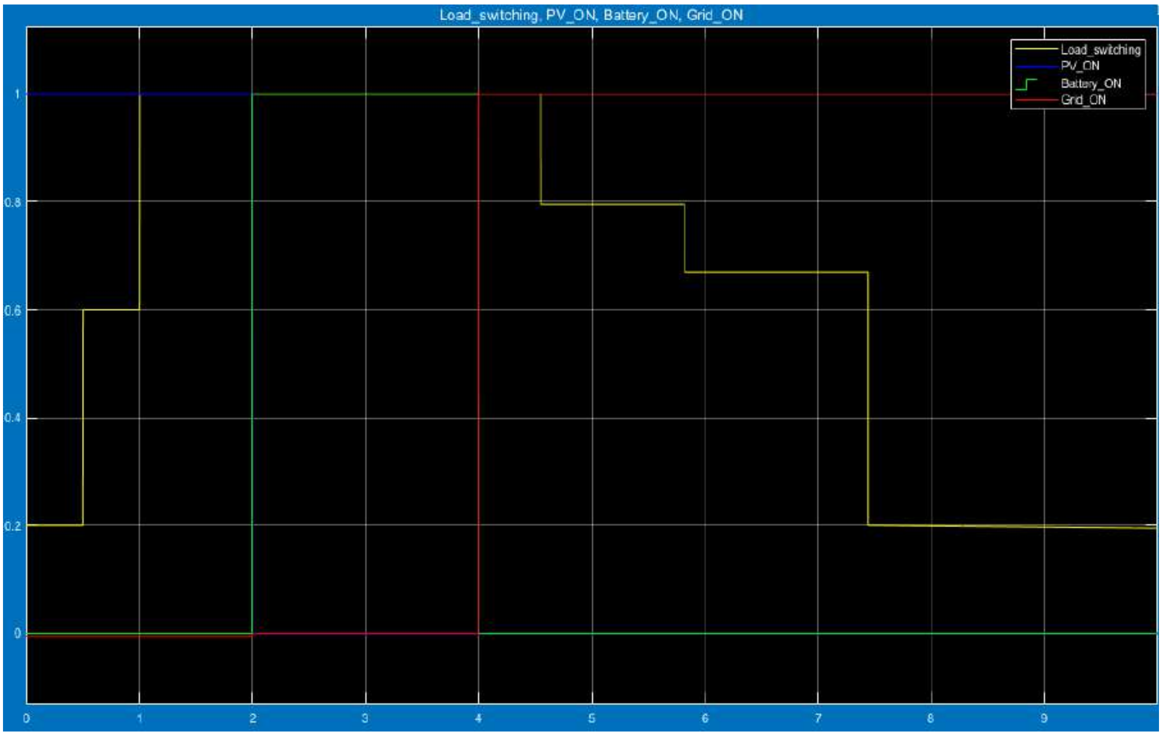

Figure 10. Switching scenario for load (yellow), PV (blue), battery (green) and grid (red)

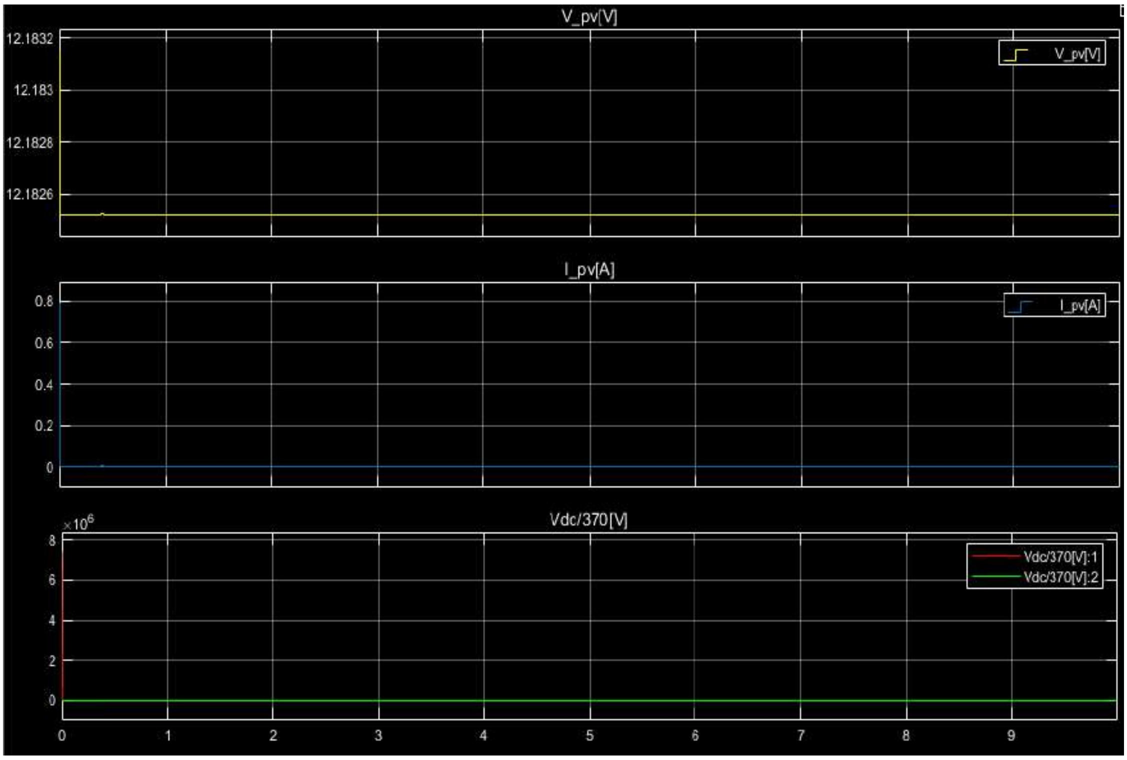

Figure 11. PV voltage, PV current and DC output voltage

4.0 DISCUSSION OF RESULTS

In this study, a grid-connected solar PV-battery energy storage system was modelled and simulated in MATLAB/Simulink environment. Environmental weather conditions i.e. solar radiation and temperature were considered when modelling the solar PV. The test was conducted at 600 W/m2 irradiance and a temperature of 26°C. The output voltage of the solar PV was 12.8 Vd.c (varying depending on solar irradiation), the battery voltage too was 12.18 Vd.c. Both the PV voltage and the battery voltage were converted to fixed 115.8 Vd.c by the DC-DC converter. The inverter converted the fixed 115.8 Vdc from the D.C-link to single-phase 240 Vrms which was synchronized to the grid voltage and supplied to the load. The load was also supplied from the grid side at a single phase 240 Vrms.

The simulation results of Fig. 10 show that the load demand of the study area rose to peak value at simulation time t = 1 to t = 4.5 then fell in discrete steps. The load was first supplied from the solar PV up to simulation time t = 2. When the solar irradiance dropped, the battery was turned on at simulation time t = 2 and supplied the load up to simulation time t = 4. The grid intervened at simulation time t = 4 when the battery power was insufficient to serve the load. The results show that the load was served at all times either from the micro sources or from the grid. The micro sources are linked to the power grid via a step-down transformer.

5.0 CONCLUSION AND FUTURE WORK

The system model is based on weather conditions and the load demand of the study area. Based on the simulated results, the system was able to manage the energy balance between the micro sources and the grid. The system is economical because it reduces the grid electricity need, prolongs the battery life and caters for possible grid failure. The energy management system used is affordable and can be applied in both domestic and industrial applications. The modelled system is environmentally friendly because it uses green energy to save the environment.

The future work of this study, which is still underway, is to implement it in real-time using Arduino-based microcontroller and to collect the weather prediction parameters remotely using Raspberry Pi 3 which will enable the prediction of next day solar power production.

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