ENERGY MANAGEMENT SYSTEM FOR PV, MICRO-HYDRO POWER WITH BATTERY STORAGE USING MATLAB/SIMULINK

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ABSTRACT

The depletion of conventional energy sources, the global quest to reduce greenhouse emissions and the exponential increase in fossil fuels prices are several reasons that there is more focus on hybrid renewable energy systems (HRES). HRES are deployed to, improve energy security, address the increase in energy demand, and mitigate against environmental degradation while reducing greenhouse gas emission to achieve socio-economic development. Power plants are particularly located closer to the load mostly in cities where they are far from rural areas. HRES microgrids provide an alternative to the grid in rural areas where it is inaccessible due to distance and terrain. The volatility of HRES requires an energy storage system for power balancing and provides continuous power flow even during power fluctuation from renewable sources. Energy management strategy is a necessity in such systems for reliability; provide good power quality, and optimal use, of distributed energy sources in the system. This paper hereby proposes an energy management system (EMS) which is a control technique for managing power flow in response to demand, supply, and storage conditions. This hybrid microgrid energy system is composed of a photovoltaic (PV) system, a micro-hydropower (MHP) system, and a Lithium-ion battery storage system to supply a 180kW load. The energy management strategy is designed to maintain the supply to the load by dispatching battery power when there is a drop in irradiance and absorb power when there is access. The system is implemented in accordance with IEC/ISO 62264 using internal control loop and primary control. The system is modelled in a Matlab/Simulink environment with various scenarios and the results obtained show immediate power injection from the battery storage system when there is a drop-in renewable power which helps to maintain power and voltage despite the fluctuation.

Keywords: renewable energy, micro-hydroelectric power plant PV system, energy management, Matlab/Simulink.

INTRODUCTION

The increase in population growth, improved standard of living, and the advancement of technologies has resulted in exponential growth in electrical energy consumption. On a global scale, 1.2 billion people, most of who reside in remote rural areas are without access to electricity. It is estimated that energy demand by 2040 would have increased by more than a quarter and renewable sources would account for 40 percent of the energy mix globally. The increase in demand has forced the rethinking of power systems. The renewable energy sources and energy storage systems are employed as an alternative so that energy can be generated closer to the places of consumption. Meanwhile, the power system infrastructure is such that large power plants are located closer to metropolitans where the load is, but far from rural settlements. The power plants utilize fossil fuels and nuclear energy sources which for most of the 20th century were abundant and less expensive. These power plants lead to pervasive environmental degradation especially the global climate change that is caused by greenhouse gas emissions. As a result, there is an urgency to curb carbon emissions without compromising universal access to modern energy, socio-economic development, employment creation, poverty reduction which are all in pursuit of realizing sustainable development goals. These reasons outlined above have yielded a spike in renewable energy focus to provide cleaner energy [1]-[3].

Growing demand for energy is the cause of the increase of distributed microgrid systems. In a standalone microgrid, there is a need to have more than one energy source for continuous power flow to meet the load. The inclusion of multitudes of sources requires energy management control for energy flow among the sources to secure reliable and optimal use of the system[4]. Energy management in microgrids is an information and control system that guarantees that the generation and distribution systems provide energy to the load optimally and at a minimal operating cost [3].

Distributed energy resources (DERs) include several different technologies such as wind, solar, diesel, fuel cell, and energy storage systems. The DERs employ advanced communication tools and power electronics devices to improve energy efficiency, power system stability, and reliability of the system. The greater penetration of renewable energy (RE) to the power system improves energy security and yields a better ecological civilization [5]. Moreover, the integration of DER in the grid or in standalone has gathered momentum and is proving to be alternatives to large conventional central power stations. However, there is a tussle with DERs due to their intermitted nature as renewable energy sources rely mostly on weather conditions and don’t provide continuous power flow [6].

In a grid-tied mode, the power imbalance is handled by synchronous generators due to power stored on the rotating masses whereas in standalone mode the DER are responsible for voltage and frequency stability within the microgrid. This however is a challenge since microgrids have low energy stored in rotating masses. Consequently, this leads to a delayed response to disturbances and yields to the power imbalance. It is for this reason that energy storage systems are employed to stabilize the voltage and frequency of standalone microgrids. It further maintains the balance of reactive and active powers[7].

Storage systems play a pivotal role to secure stable power flow. They also assist in frequency regulation if sudden power variation is experienced. Energy storage systems require a quick response to the disturbances in the standalone microgrids. The response is determined by the energy management using different control methods. These methods are based on several factors such as matrix-based programming language in Matlab/Simulink, hybrid optimization by generic algorithms in HOMER, and Java environment platform for multi-agents in JADE [3].

Research in different energy storage systems to mitigate power imbalance, maintain voltage and frequency is vast. Hydrogen (H_2) gas can be used in a form of storage produced through electrolysis when there is surplus electricity. Consequently, the H_2 produced will be utilized by fuel cells to mitigate blackout during high demand [8].

The coupling effect of the surge tank used in hydropower system stability with the grid is explored. Surge tanks are a vessel look-a-like container that mitigates against overpressure effects or water hammer as a safety measure. Furthermore, the vibrations are investigated and concluded that for free vibration equation of hydropower with a surge tank coupled to a grid under step load disturbance requires a ninth order linear homogenous differential equation [9]. Microgrids have a variety of applications in the electrical and energy space and the need for EMS is crucial for optimization challenges. Therefore the predictions of demand and available energy are essential. In [10] the robust EMS is utilized using fuzzy prediction interval model(FPIM) to represent the non-linear and uncertainty of availability of energy from the wind source. FPIM ensures a range of probabilities that trajectories of uncertainties belong. The ranges are upper and lower boundaries of available energy. The power balance of 95% is attained despite wind power fluctuations. This type of control is suitable for microgrids where the main sources of power are intermittent such as solar and wind.

This paper presents a power plant driven by renewable energy sources employing the PV system, MHP, and the lithium-ion battery storage system that is implemented on Matlab/Simulink environment based on a 180kW load for rural settlement. The energy management algorithm is employed to help in the interaction between different systems and maintain the balance between supply and demand of the system.

The aim is to have an energy management control system using proportional-integral (PI) control to maintain power flow and voltage during the disturbances. The control provides satisfactory performance as it takes 0.8 s for the system to reach a steady-state. It further shows no mismatch during a drop-in renewable power due to the quick charge/discharge control method.

The paper layout is as follows: Section II presents the related work from different studies on EMS. Section III focuses on system modelling, operation, and components that constitute the system. Section IV detailed the results and discussion while Section V focusses on key findings and concludes the paper.

RELATED WORK

There are several studies conducted to study various ways in which energy can be managed. Authors in [11] modelled an AC hybrid system power system with wind-solar and pumped storage hydropower. The focus is on the integration of pumped storage to the power system with effects of shaft vibrations and the governing strategies which increase dynamic risk and leads the disturbances. The system is modelled in Matlab/Simulink to mitigate those disturbances by unifying the hydro-turbine governing system and the hydro-turbine generator unit. The three-phase short circuits are mimicked to test the feasibility of the pumped storage when integrated into the hybrid system. The results indicate that the current and voltage of the pumped storage briskly gets to normal operation after the fault has been cleared. Moreover, the results further indicate that the pumped storage can quell fluctuations from solar and wind power.

In [12], both the HOMER and Matlab/Simulink are used in a microgrid that is made up of MHP, PV and they are grid-tied. When the author optimizes the system HOMER is utilized using the local renewable energy available of GunungNago to check for the combination that would yield the lowest cost and most reduction in carbon dioxide emissions. The baseload profile, availability of water resources, and solar radiation were used to simulate the possible microgrid. The possible solutions from however needed costly initial capital cost and the system was then modelled in Matlab/Simulink. This system however indicates a lot of power fluctuation throughout the simulation from the MHP. The battery power during the load fluctuations is not shown to validate the response time.

The authors in [13] illustrate the combination of several renewable energy sources that helps in the accessibility of electricity, especially in remote areas. Despite that the coexistence of more power sources specifically renewables to form microgrids leads to system instabilities. This is due to different inertias and control strategies. The focus of the research is the hierarchal controller of the hybrid microgrid to accomplish the smooth parallel operation. It further dealt with power-sharing performance and PV and battery being the PQ bus to inject the required active and reactive power to the local grid. The hydropower is operated as the slack bus to regulate the voltage amplitude and the frequency. The system tested different scenarios where the load is removed from the system or added to test the response to maintain the frequency of the system. In instances where the load is suddenly removed the frequency increases from 49.99Hz to 49.995Hz due to hydraulic power output decrease and experience a 0.001 per unit spike. The different scenarios have tested the robustness of the system and indicate that the system can operate effectively on parallel operations with varying loads.

In this study the research is based is on Mae Sariang microgrid using FLC control on the battery energy storage system (BESS). Quest for a quick response from energy storage systems to maintain both the frequency and voltage using energy management techniques is being explored. The system consists of the PV array, diesel generator, hydro generator and, BESS. The system is modelled in DIgSILENT Power Factory software using FLC to stabilize frequency and voltage fluctuations with BESS. The system is analysed on a standalone microgrid to test how fuzzy logic control performs to control active and reactive power injection from the battery storage system to mitigate the frequency and voltage fluctuations. [7]

Nowadays there is a significant amount of research conducted on energy management control. Authors in [14] modelled a hybrid microgrid system with the wind, photovoltaic (PV) diesel generator with a battery storage system with an intelligent supervisory control based on fuzzy logic control for power balance. Authors [15] focusses on energy management on residential load with varying demand using simpower toolbox from Matlab/Simulink also considering wind, PV, and Lithium-ion battery storage. In [16] the focus is to meet DC loads demand utilizing PV and battery storage to form a standalone hybrid microgrid system and the energy management control is using FLC. Authors in [8] use fuzzy logic for energy management control of a system that comprises of PV array, an electrolyzer, proton exchange membrane, and hydrogen tank.

Previous studies have suggested that the combination of PV and Micro-hydropower can help in the stability of the power supply as hydropower and pumped storage has a great regulating ability. However, this too poses a challenge of not meeting the load hence the requirement of a storage system [2-5].

SYSTEM DESCRIPTION

System Mathematical Modelling

The system consists of two power sources which are PV array, MHP, and battery storage systems as the backup. The PV array provides 102.4 kW of electrical power and consists of the DC-DC boost converter with maximum power point tracking (MPPT) to be able to extract maximum power from the array and voltage source converter. The MHP consists of the excitation system, synchronous generator, turbine, and the governor and will supply a consistent power of 95kW. Furthermore, there is a rectifier as an interface device for the integration of MHP, PV, and Battery storage system as illustrated in Figure-1. The battery storage system either absorb excess power or dispatch when the power sources are producing less. The PV system contributes

The system is connected to the AC load via a voltage source converter (VSC). The inverter uses a phase-locked loop (PLL) to maintain the frequency and phase angle of the voltage. The control scheme is made up of voltage and current regulators using PI control to improve power factor of the system. LC filter are used to quell harmonics produced by the inverter.

The PV is the primary power source of the system therefore; the irradiance will be varied to mimic real-life scenarios. The Li-ion battery storage with a bidirectional buck-boost converter is employed as a backup system to maintain continuous power to the load and maintaining 750 volts on the DC bus. Insulated-gate bipolar transistors (IGBT) are employed as switching devices to maintain the voltage at the DC link. MHP is producing a constant power with a flow rate of 0.27m^3/s and a hydraulic head of 45m.

In accordance with IEC/ISO62264 which is an international standard for supplier and manufacturer communications, the microgrid needs to adapt to this standard. There are four levels of control which are the internal control loops, primary control, secondary control and tertiary control. The two controls that have been utilized in this system are the inner control and the primary control. The internal control loop employs power electronics devices like VSC in managing frequency and voltage inside the microgrid. In primary control, the storage system is controlled by the bidirectional converter based on voltage fluctuation using PI control.

Table-1. System characteristics.

PV array	
Max. Power	102.4kW
Max. Voltage	750V
MHP	
Max. Power	100kW
Max. Voltage	750V
Battery Storage	
SOC	50%
Voltage	450V
Max. Power	70kW

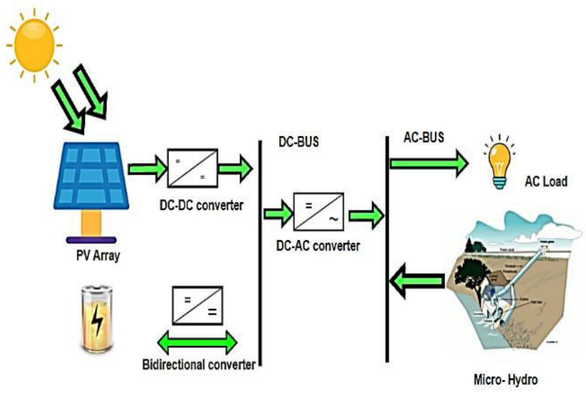

Figure-1. System architecture.

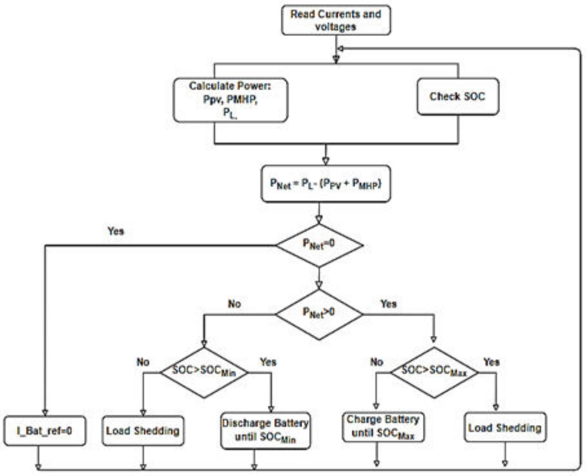

Figure-2. Energy management algorithm.

Micro-Hydro Power System

The potential energy of water due to the hydraulic head is converted to kinetic energy which then yields impulse force on the turbine blades producing mechanical energy. As a result, the mechanical energy is converted to electrical energy by the generator. The MHP is a plant that can produce about 5 Kilowatt (kW) to 100kW of power and has several advantages as compared to large hydropower plants. MHP is less capital intensive, does not degrade the environment by the construction of bigger dams, does not require major political decisions for it to be implemented, and requires fewer costs associated with the relocation of inhabitants.

The MHP system consists of two major sections which are the mechanical section and the electrical section. The mechanical section consists of a hydraulic turbine and the governor which is a system that regulates the turbine rotating speed using the servomotor. The servomotor determines the opening of the gate using the PID controller to adjust the error due to the difference between the reference rotational speed and the actual turbine speed. The droop characteristics use two alternatives which are dependent on the binary signal d_{ref} whereby the top position uses negative feedback whilst the lower position the droop signal is the difference of P_{ref} which is the reference power and the actual measured power.

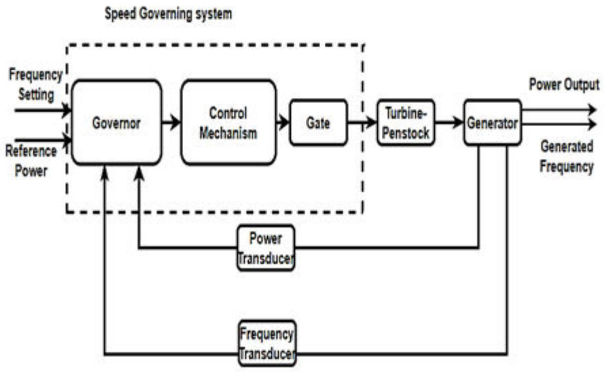

Figure-3. MHP schematic diagram.

The mechanical power produced by the hydro turbine is proportional to the pressure head and the volumetric flowrate [17]. The power generated is described by:

$$P_t = \rho g Q H \tag{1}$$

Eqn.1 represents the ideal turbine, due to the losses in the turbine; it is therefore not 100% efficient. The equation is however modified to cater for other losses like mechanical friction loss and internal pressure loss. Modelling of a non-linear turbine with the assumption of non-elastic water column after determining the base head which is the total static head and the base gate which is when the gate is fully opened, the per-unit volumetric flow rate is given by Eqn.4 [18], [19].

$$P_m = A_t H(Q - Q_{NL}) \tag{2}$$

$$A_t = \frac{Turbine\ Power(MW)}{Generator\ Power(MVA) H_r (Q_r - Q_{NL})} \tag{3}$$

$$Q = G\sqrt{H} \tag{4}$$

Where P_m is Mechanical power from the shaft in W, Q is the volumetric flow rate, Q_{NL} is the volumetric flow rate with no load in m^3/s, G is the gate opening in radians (rad) and H is the net head in m.

Excitation System and Generator

The electrical section is made up of an excitation system and a synchronous generator. The excitation system's core function is to supply direct current to the field windings of a synchronous generator. This system helps to protect and control field voltage and current by voltage and reactive power flow control thus mitigating against exceeding capability limits of the synchronous generator [20].

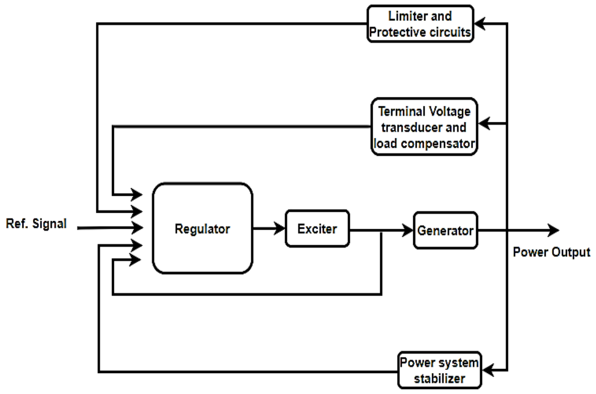

Figure-4. Excitation block diagram.

Electrical Machines work on a principle known as Electro-Mechanical energy conversion which converts electrical energy to mechanical energy and vice versa. Generators change the mechanical energy from the turbine to electrical energy. The principle of operation of the generators is based on Faraday's law of electromagnetic induction which states that electromotive force(e.m.f) will be induced in the conductor coil when a current-carrying conductor is placed in a rotating field which is due to the angular velocity(ω) caused by the prime mover and cuts the fluxes [21].

Photovoltaic Cell

The photovoltaic cell is made up of a semiconductor material that transforms sunlight into electrical energy in what is referred to as the photovoltaic effect. Photons are absorbed from the sunlight and generate free electrons. When electrons are excited by light energy, they subsequently get freed, therefore the built-in barrier in the cell enables these electrons to produce a voltage that is used to drive current through the circuit. Silicon is the most used semiconductor material in PV applications which are multi-crystalline silicon and monocrystalline silicon for high-efficiency solar cells [22], [23].

As seen in Eqn. 5, R_s is the losses due to electrical contact and cell material resistivity, I_{ph} is the photovoltaic current produced because of sunlight by the solar cell, R_p is losses at the p-n junction, I_D is the current in the diode and I_{pv} is the current at the terminals of a solar cell [8].

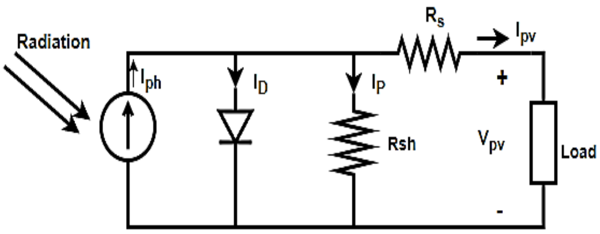

Figure-5. Equivalent photovoltaic cell.

According to Figure-5 above, the voltage-current characteristics of the PV cell are given by:

$$I = I_{ph} - I_s\left\{exp\left(\frac{V+IR_s}{A}\right) - 1\right\} - \frac{V+IR_s}{R_{sh}} \quad (5)$$

$$A = \frac{mkT_c}{q} \quad (6)$$

Where *K* is the Boltzmann's constant in J/K, A is the thermal voltage in V, T_c is cell temperature in K, V is the voltage, *m* is the identical factor and *q* is the electric charge.

Battery Storage

Renewable energy system due to their intermittent nature requires energy storage system to maintain the stability of the system by balancing the power. In this system, the battery storage system is used and lithium-Ion batteries are chosen. The lithium-ion batteries are employed so to have a reliable hybrid system due to their high energy efficiency, long lifespan, high power density, and high reliability. Lithium-ion can be utilized as active filters improving power quality, protecting the loads against voltage sags and harmonics [24] The lithium-ion batteries system will comprise of two components which are the battery bank and a bi-directional DC-DC(buck/boost) converter with two switches to control power flow[25], [26]. The buck/boost converter assists in matching the voltage from the batteries to the renewable source, it further controls the charging and discharging of the battery [27].

The batteries need to be kept in good a condition, which means a required need for energy management to control the charging and discharging to have a longer battery lifespan. The scenarios. If these conditions are not maintained, it reduces the capacity of the battery. In addition to a battery storage management system that monitors the voltage, current and, temperature to keep the state of the battery in good condition and balancing the charge to the cells, to keep the cell voltage constant. The control of the battery system can be done by the microcontroller which monitors both voltage and current depending on the state of charge (SOC) and the ambient temperature [28].

The SOC is the indication of how much power the battery still has and it is given by Eqn 7.

$$SOC = 100(1 - \frac{\int_0^t idt}{Q}) \quad (7)$$

Where I is the battery current (A) and Q represent the battery capacity (Ah).

The Lithium-ion battery discharging and charging model is given by Eqn (8) and (9) respectively

$$V_{batt} = E_o - R \times i - K\frac{Q}{Q-it} \times (it + i^*) + Aexp(-B \times it) \quad (8)$$

$$V_{batt} = E_o - R \times i - K\frac{Q}{it-0.1Q} \times i^{*} - K\frac{Q}{Q-it} \times it + A\exp(-B \times it) \qquad (9)$$

Where:

V_{batt} = Voltage battery (V)
E_o = Battery constant voltage (V)
K =Polarisation constant (V/(Ah)) or polarisation resistance (Ω)
Q =Battery Capacity (Ah)
it =Actual battery charge (Ah)
A =Exponential zone amplitude (V)
B =Exponential zone time constant inverse $(Ah)^{-1}$
R =Internal resistance (Ω)
I =Battery current (A)
i^{*} =Filter current (A)
exp = Expontional zone voltage (V)

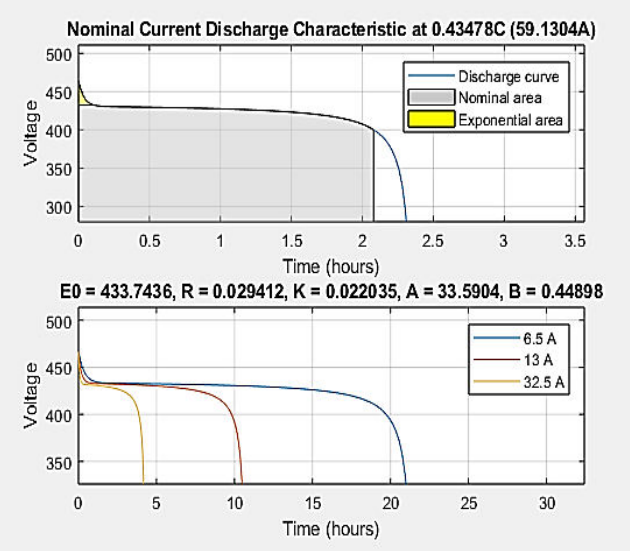

Figure-6. Lithium-ion battery characteristics.

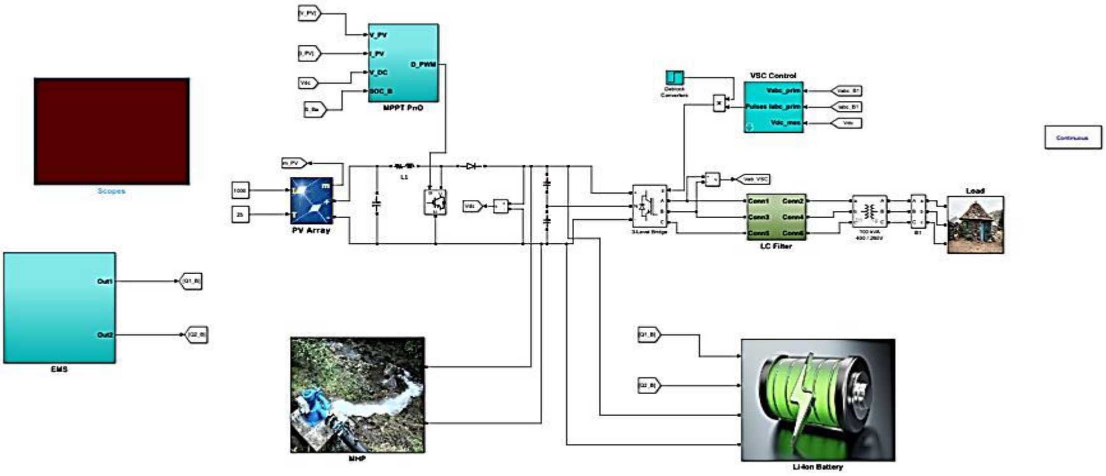

Figure-7. System model.

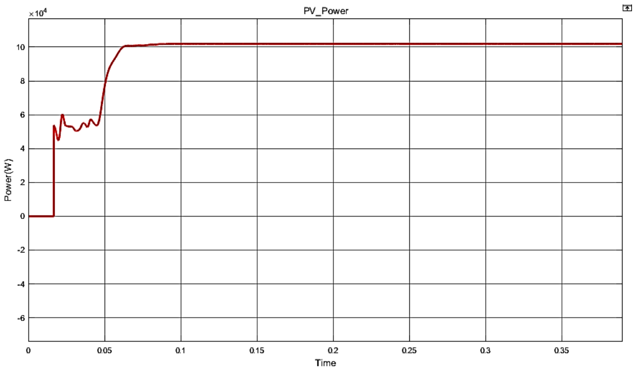

Figure-8. PV transient time.

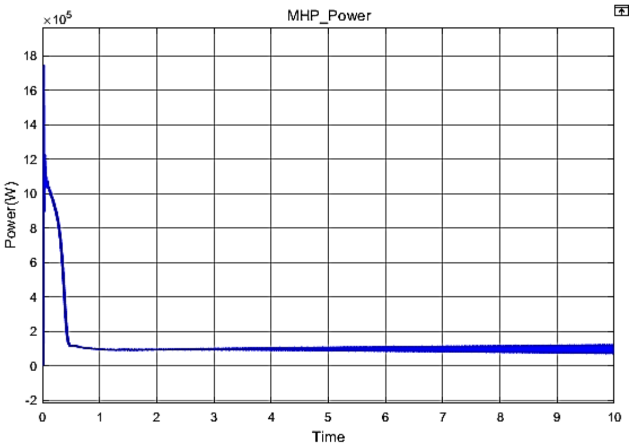

Figure-9. MHP power.

MHP power spike is a result of sudden mechanical torque because of the kinetic energy of water on the blades, there is a spike in rotational speed hence the exponential power at t=0 sec to t=0.8 sec where the oscillations are damped, and steady-state is reached at t=1 sec.

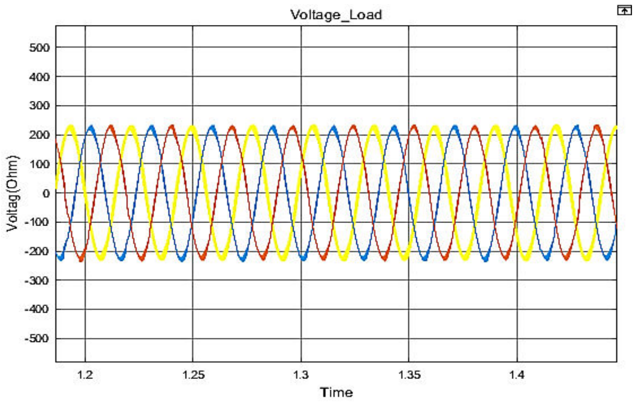

Figure-10. Load voltage.

Figure-11 above shows that the voltage power is kept constant at 230 V

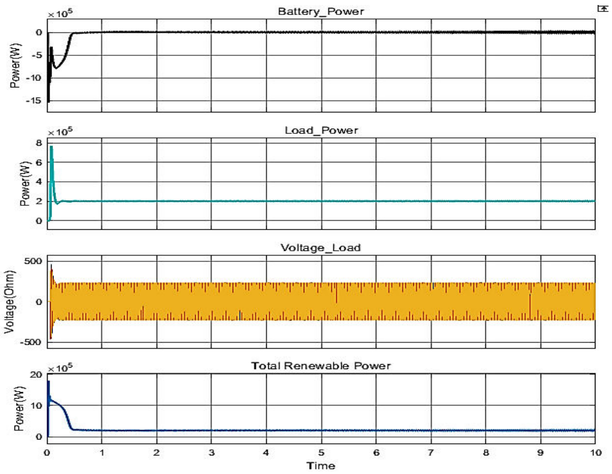

Figure-11. Battery, load, and total renewable power and voltage at the load.

Scenario 2

The second scenario is when the irradiance is varied from 1000W/m^2 to 400W/m^2 at a time then back to 1000W/m^2 as seen in Figure-13(a) below. In the first four seconds, the irradiance is 1000W/m^2 then from four to seven seconds it is dropped to 400W/m^2. The irradiance then increases again to 1000W/m^2. The MHP is 95kW and the power from t=0 to t=4 is 102.4kW which makes the total power from the renewables be more than the load hence the battery charges and the SOC moves from 50% to 50.14%. The irradiance drops at t=4 to t=7 and the SOC decreases from 50.14% to 50.08% and the battery dispatches power as depicted in Fig. 13(f) by battery pow and voltage on the AC side does not change because of the compensation power by the battery illustrated in Figures 13-15. The irradiance goes back to 1000W/m^2 at t=7 and the battery then charges again as the Power is more than 180kW required to meet the load.

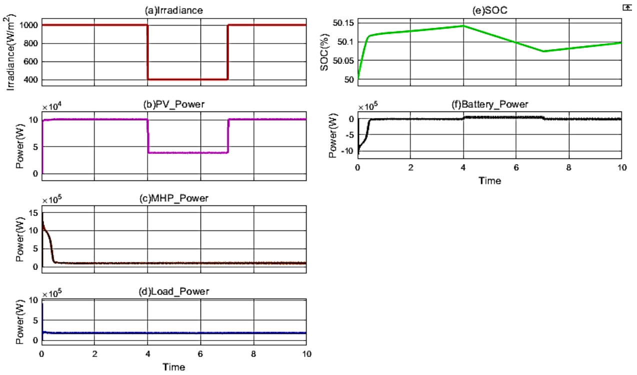

Figure-12. PV, MHP, battery and load power with varying irradiance.

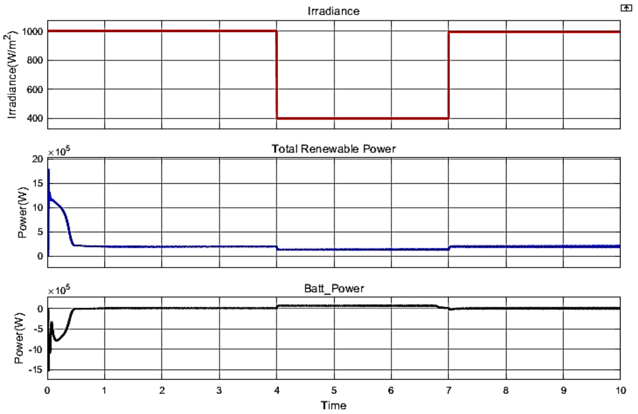

Figure-13. Battery response during power drop.

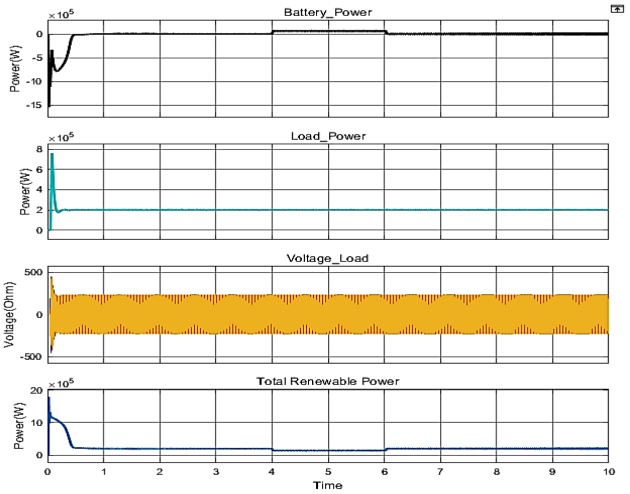

Figure-14. System performance during power drop.

CONCLUSIONS

Renewable energy microgrids are very important in reducing carbon footprints and can be very helpful in rural electrification programs as islanded microgrids. This study employed the PV system and the MHP system to cater to the load of 180kW and the Li-ion battery storage to cater for the mismatch between supply and demand. The aim was to develop an energy management control for mitigating the mismatch between demand and supply. The

IEC/ISO 62264 was implemented using internal loop control utilizing power electronic devices and the primary control employing Lithium-ion storage system with bidirectional converter with PI control for the microgrid control. The scenarios investigated show that the systems energy management can provide good energy share amongst power sources. The system transient time is 0.8 sec to stabilize mainly because of the dumping of oscillation from the MHP system. Future work will be focussing on the complexity of varying loads and all power source inputs and test the robustness of the system in terms of EMS control strategy and validating this EMS with real-time simulations.

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