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Energy Management System for Hybrid PV-Wind-Battery Based Standalone System

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Abstract

This research proposes an Energy Management System (EMS) for a small-scale Hybrid PV-Wind-Battery based standalone system.PV energy and wind energy are used as primary energy sources, with the battery serving as a backup supply. The Solar Energy Conversion System (SECS) and the Wind Energy Conversion System (WECS) are modeled and simulated separately with the help of different boost and buck converters. This work also discusses the design, simulation, and implementation of a multi-source renewable energy system MPPT control technique based on a Fuzzy Logic Controller (FLC).Renewable sources are varied according to the solar irradiance and wind speeds while loads are kept constant.The DC load is connected directly to the DC bus, while AC load is connected via inverter. After the addition of the both system, if the power cannot sustain the load due no wind and foggy atmosphere, the battery system is incorporated to support the system. It incorporates the EMS using fuzzy logic for the power balance of the system. For the better performance optimization, operational efficiency and the reliability of the system, hybrid PV-WT-Battery system in modeled and simulated in MATLAB/Simulink. This system is for standalone mode, it provides the foundation for further study with interface to the grid and many other problems.

Keywords

Solar Energy Conversion System(SECS), Wind Energy Conversion System(WECS), Energy Management System(EMS), Fuzzy Logic Controllers(FLC), MATLAB/Simulink

1. Introduction

The widespread use of fossil fuels moves the earth to clean and green energy. Where the grid is not available or transmission towers cannot be installed, renewable energy sources are the most critical as distributed generation sources.PV and Wind power are considered as the finest alternatives among the various renewable sources.[1].As both of these energy sources are intermittent, the usage of an Energy Storage System (ESS) is required in stand-alone applications as backup supply.[2].By combining the PV and WT power generation, it overcomes the drawbacks of their unpredictable nature and instability of the output power is compensated [3, 4, 5].

A hybrid PV-Wind-Battery energy storage system is simulated in MATLAB/Simulink to test the state of charge (SOC) control [6].The aim of this study is to design and build a small-scale PV-Wind-Battery stand-alone renewable energy system.An EMS is presented to maintain power balance in a standalone system and to enable flexible and configurable control for various wind speed and solar irradiance fluctuations in renewable energy sources.

2. System Description

The structure of the hybrid energy system is presented in Figure 1.The proposed system can be divided into four parts; i) Solar Energy Conversion System (SECS) ii) Wind Energy Conversion System (WECS) iii)Battery Storage System (BSS) and iv)Energy Management System (EMS) with single phase ac and dc load,.

At varied solar irradiation and wind speeds, the PV array and wind turbine produce energy for the load.PV array is operated at the MPP using the FLC. The PV voltage is step up using DC-DC boost converter and finally connected to DC Bus. The WECS consists of a wind turbine with a PMSG that is also run at MPP utilizing a FLC. The ac power output from the PMSG is rectified using AC-DC converter which is then step down using DC-DC buck converter and connected to the DC Bus.When the generated energy is insufficient to meet the demand,the excess energy which is stored in the battery is supplied to the load.Battery charge controllers keep the battery voltage within a certain range,preventing from over charging and over discharging.The AC load is supplied through inverter and DC load is connected to the DC Bus.The DC and AC loads are kept constant and only the renewable energy varies.

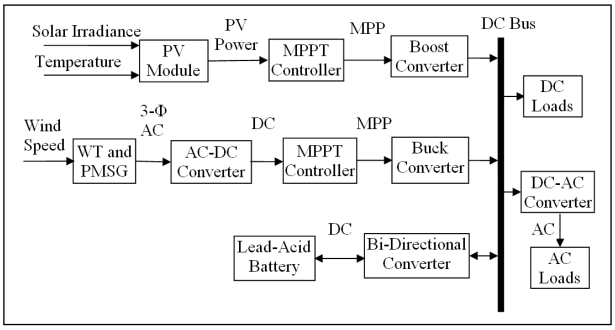

Figure 1: System Block Diagram

2.1 Solar Energy Conversion System (SECS)

SECS contains a PV module,a boost converter and Fuzzy Logic based controller for MPPT.

2.1.1 PV Cell Model

A conventional single diode model of a PV cell as shown in Figure 2.

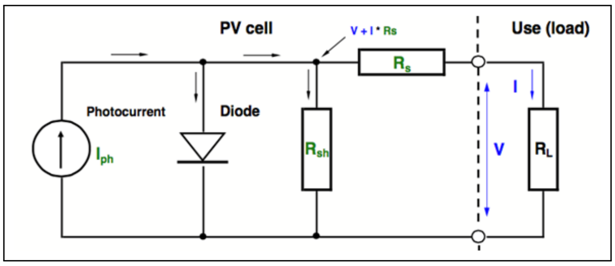

Figure 2: PV cell equivalent circuit

The characteristic equation of the model is as shown in equation 1 [7].

$$I = I_{ph} - I_o\left(\exp\left[\frac{V+IR_s}{N.V_t}\right]-1\right) - \frac{V+IR_s}{R_{sh}} \quad (1)$$

where Iph is light photo current,N is the ideality factor of the diode,Io is reverse saturation current,V is the voltage across the diode,Vt is thermal voltage,Rsh and Rs are the shunt and series resistors of the cell respectively.

2.1.2 DC-DC Boost Converter

The principal objective of converter is impedance harmonizing of the load with output of the solar array. When load resistance equals to source resistance, we can extract maximum power from the PV device, so impedance matching is a must.Based upon various experiments, boost converter outperforms all the other converters [8].The boost converter circuit diagram is shown in Figure 3.

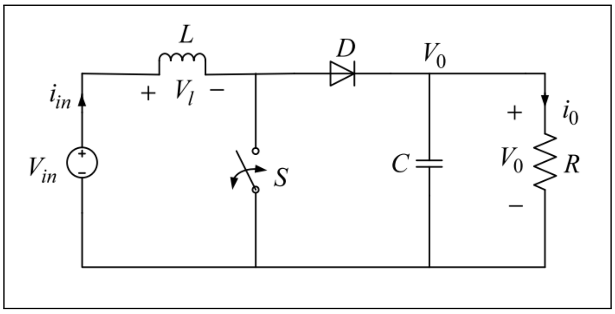

Figure 3: Circuit Diagram of Boost Converter

The values of duty cycle, inductor and capacitor of the boost converter is defined by the equation 3.

$$\begin{aligned} D &= 1-\frac{V_{in}}{V_o} \\ L &= \frac{V_{in}\times(V_o-V_{in})}{\Delta I_l \times f_s \times V_o} \\ \Delta I_l &= (0.2 \text{ to } 0.3\ )\times I_{\mathrm{o\ (max)}}\times\frac{V_o}{V_{\mathrm{in}}} \\ C &= \frac{I_{\mathrm{o\ (max)}}\times D}{f_s\times\Delta V_o} \end{aligned} \quad (2)$$

where D is duty cycle,V is voltage across the diode, $Io(max)$ is maximum output current, Vin is input voltage,fs is switching frequency,ΔIl is inductor ripple current and ΔVo is output voltage ripple.

2.1.3 SECS Fuzzy Logic MPPT Controller

The MPPT controller objective is to track and extract the maximum power possible from PV array at a given solar irradiation and temperature. The fuzzy logic technique is used in the MPPT control system for our PV.Fuzzy logic provides the advantages of functioning with general inputs. It consists generally three stages:

fuzzification, rule base and defuzzification as shown in Figure 4 [9]. The numerical input variables are fuzzified and then converted into language variables using membership functions. The changes in voltage and current corresponding to the two examining time moments are the fuzzy system's inputs. These inputs are prepared by the fuzzy controller, and the duty cycle is the output yield, which shifts on the region of the $Ipv \times Vpv$ curve.

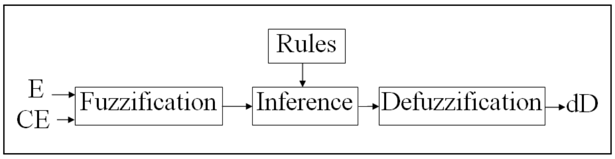

Figure 4: Structure of Fuzzy Logic

2.2 WIND ENERGY CONVERSION SYSTEM (WECS)

A wind turbine, a PMSG, an AC-DC converter, a DC-DC buck converter and a fuzzy logic based MPPT controller comprises the WECS.

2.2.1 Wind Turbine System (WTS)

The power developed from the wind is [10] by equation 3.

$$P_w = \frac{1}{2}\rho A v^3 C_p(\lambda,\theta) \tag{3}$$

Here A is rotor blades area swept (m^2),ρ is density of air (kg/m^3), and v is wind velocity (m/s). Cp is power coefficient which depends on pitch angle (θ) and tip speed ratio (TSR, λ).

As of low operational and low maintenance cost, PMSG is preferred over other generators.The generator output relies on the wind speed so a variable speed wind turbine is chosen for given model.

The wind turbine includes a variable-speed pitch controller to prevent rotor overspeeding and protect the electrical system. [11].As a result, the pitch angle can be used to adjust the power output of a wind turbine.

The three-phase ac output of the generator is rectified to single-phase dc by using rectifier circuit.

2.2.2 DC-DC Buck Converter

It is a DC-to-DC power converter which steps down the voltage while the current is stepped up with respect from its input to output. Buck converters are more efficient than linear regulators. The basic principle of this converter has the current in the inductor controlled by a transistor and a diode. Ideally, the switch and diode are considered to have zero voltage drops when on and zero current flow when the switch if off and the inductor has zero series resistance.Buck converter circuit diagram [8] is shown in Figure 5.

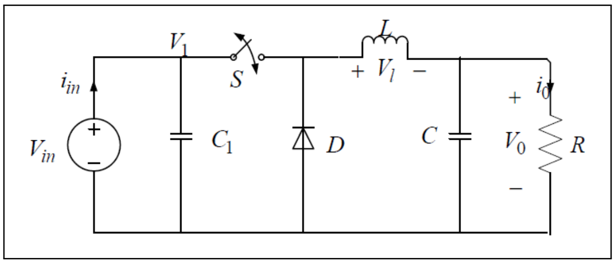

Figure 5: Circuit Diagram of Buck Converter

The values of duty cycle, inductor and capacitors of the buck converter is [12] defined by the equation 5.

$$\begin{aligned} D &= \frac{V_o}{V_{in}} \\ L &= \frac{V_o \times (1-D)}{f_s \times \Delta I_l} \\ C &= \frac{1-D}{\frac{\Delta V_{co}\times 8\times L\times f_s{}^2}{V_o}} \\ C_1 &= \frac{I_o}{\eta \times f_s \times \Delta V_{in}}\left(\frac{D}{\eta} - D^2\right) \end{aligned} \tag{4}$$

where D is duty cycle, fs is switching frequency , Vo is output voltage, Io is output current, Vin is input voltage, ΔIl is inductor ripple current, η is efficiency, ΔVo is output voltage ripple, ΔVin is input ripple voltage and ΔVco is output capacitor ripple voltage.

2.2.3 WECS Fuzzy Logic MPPT Controller

The wind turbine does not always work in optimal condition because of non-linear system. As a result, an MPPT controller is required to track the maximum power point as the wind speed changes. The Fuzzy Logic control system is presented in this paper.The voltage and current output of the PMSG serves as the input of the fuzzy logic and provide the duty cycle based on the specified fuzzy rule as output for extraction of maximum power from turbine. [9].

2.3 Battery Storage System (BSS)

A Lead-Acid Battery and a Bi-Directional converter are included in the BSS.

2.3.1 Battery System

The battery is critical to the BSS because it allows it to store surplus energy generated by renewable sources and deliver it when the energy supplied by solar and wind energy sources is insufficient to meet load demands. Lead-Acid batteries are more efficient and less expensive than other batteries in hybrid energy systems. [11].The state of charge (SOC) [10] is given by the equation 6.

$$SOC = 100\left(1 + \frac{\int I_{battery}dt}{Q_b}\right) \tag{5}$$

where $I_{battery}$ is the battery current and Q_b is the battery capacity. The battery works on charging and discharging modes which can be defined by their SOC limits.

$$SOC_{min} \leq SOC \leq SOC_{max} \tag{6}$$

2.3.2 Bi-Directional DC-DC Converter (BDC)

Solar and wind energy is stored in batteries during the periods of excess generation and utilized during periods of energy shortfall. In these applications, a bi-directional DC–DC converter is utilized to transport power in either way between two sources [13] .Figure 6 shows the circuit diagram of BDC.

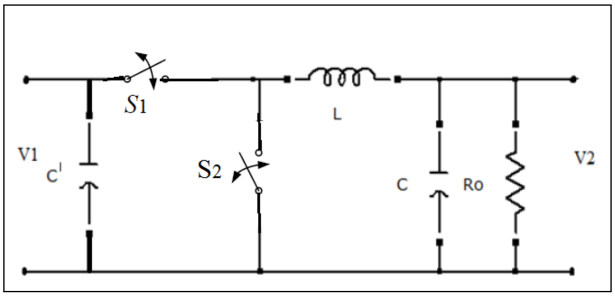

Figure 6: Circuit Diagram of BDC Converter

When switch $S1$ is turned on buck mode operates and when switch $S2$ is turned on boost mode comes into operation.

2.4 Energy Management System (EMS)

The principal controller in standalone systems is the EMS, which organizes and controls all control operations. The battery's bidirectional DC-DC converter runs in charging or discharge mode and maintains a constant DC bus voltage with coordination of EMS. Under changing generation of energy from renewable energy sources and load demand conditions, the power in the system must be balanced. The following is the power balance equation.

$$P_w + P_{pv} = P_L + P_{battery} \tag{7}$$

where P_{pv} is power from PV, P_w is power from wind,P_L is power of load and $P_{battery}$ is power of battery.

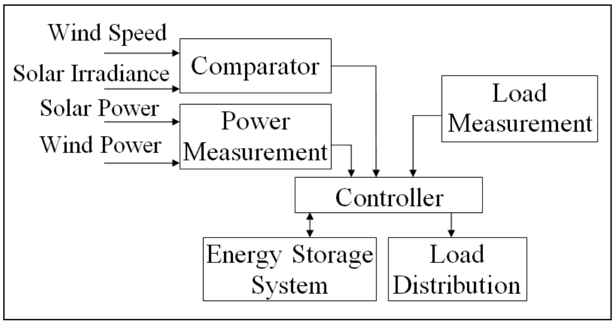

Figure 7: Block diagram of EMS controller

The controller in Figure 7 acts as a governor, which governs the switching operation from one operation mode to another depending upon the availability of the wind, irradiance level of the sun and the demand of the load.The error of the sum of generated power and load power is feed to controller and decides the mode of operation and control of battery system as well as the load distribution.

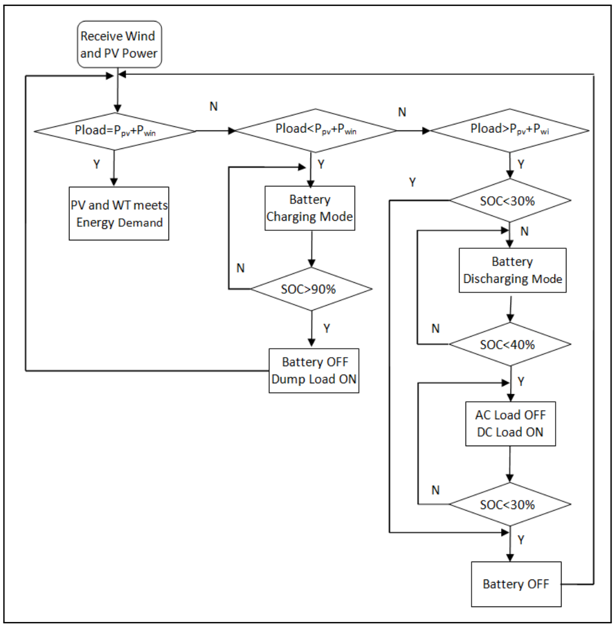

Figure 8: Control Algorithm for Battery Control

The control algorithm for the Battery Control is provided in the flowchart shown in Figure 8. In this process, we compare the load power demand (which is sum of DC Load and AC Load) with the generated power (which is sum of wind power and solar power). When the generated power equals the load demand, then we assume the system as steady state and the supply meets the demand. Similarly, if generated power is more than load power, battery is in charging mode until it is 90 % charged. If the generated power is still more than the load power even when the battery is 90% charged, the excess energy is supplied to the dump load and the battery charging is off at 90%.But however, if the generated power is few than the load demand, the system is powered with battery, when the SOC is less than 40% at that AC load (AC Load is less priority than DC Load) cut off and only DC load is powered. If the generated power is still less than the load power even when SOC is 30%, then we have to shed the both loads from the battery. Based on these functions, the control algorithm for the Battery Control is developed.

3. Results and Discussion

Simulation of the Hybrid PV-Wind-Battery system which was done in MATLAB/Simulink(R2017a) environment.Simulation was performed at variation of PV and wind power with a constant dc and ac load condition as per solar irradiance and wind speed. The simulation time for the results is 1s.

3.1 Solar Energy Conversion System(SECS)

Figure 9 shows the simulation diagram of SECS and Figure 10 shows the MPPT Power at different values of irradiance (0.25 kW/m^2,0.5 kW/m^2, 0.75 kW/m^2 and 1 kW/m^2) at constant temperature of 25^0C.When solar irradiance is 1 kW/m^2, the power is around 60 Watt with output voltage of 48 volts .

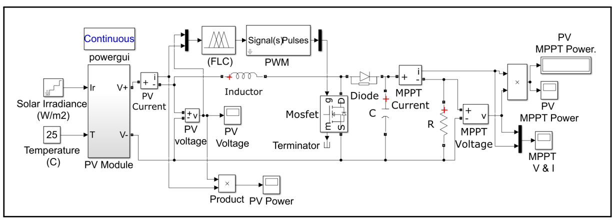

Figure 9: Solar Energy Conversion System

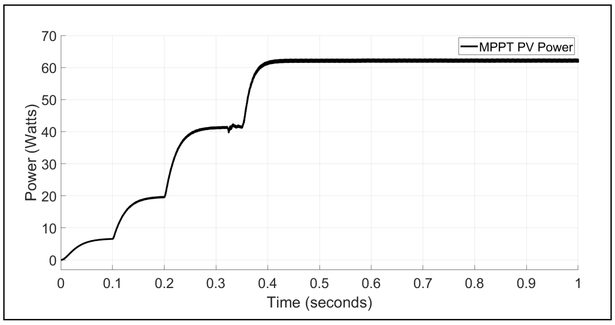

Figure 10: Photo Voltaic MPPT Power

Table 1 shows the Solar Energy Conversion System (SECS) simulation parameters of the PV module and Boost converters.

Table 1: SECS Parameters

Parameter	Value	Unit
Nominal Power	60.8	Watt
OC Voltage	48	Volts
SC Current	1.8	Ampere
MPP Voltage	47.5	Volts
MPP Current	1.28	Ampere
Inductance	161	mH
Capacitance	550	μF
Resistance	40	Ω

The control fuzzy rules of SECS are presented in Table 2. LC, MC and HC are input currents, LV, MV and HV are the input voltages and output duty ratio are LMD, MMD and HMD.

Table 2: Control Fuzzy Rules for the SECS

	LC	MC	HC
LV	HMD	HMD	MMD
MV	HMD	MMD	MMD
HV	MMD	MMD	LMD

3.2 Wind Energy Conversion System(WECS)

Figure 11 shows the WECS simulation model and Figure 12 shows the MPPT wind power at different wind speeds.The speed of wind are 5 m/s, 7 m/s, 9 m/s, 11 m/s and 12 m/s.When the wind speed is 12 m/s,the maximum power from the wind is achieved which is around 480 Watts with output voltage of 48 volts.

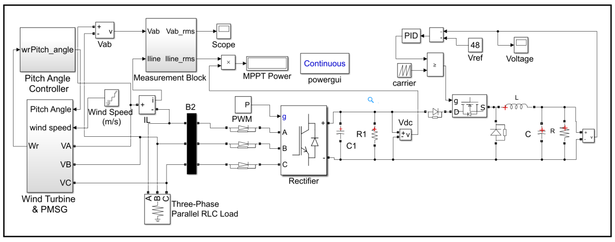

Figure 11: Wind Energy Conversion System

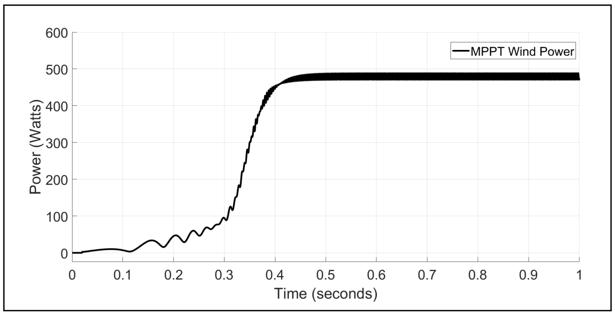

Figure 12: Wind MPPT Power

Table 3 shows the Wind Energy Conversion System (WECS) simulation parameters of the WT,PMSG and Buck converters.

Table 3: WECS Parameters

Parameter	Value	Unit
Nominal Power	480	Watt
No. of Phases	3	
Base Wind Speed	12	m/s
Capacitance(C1)	47	mF
Resistance (R1)	10	KΩ
Inductance (L)	1	mH
Capacitance (C)	470	μF
Resistance	10	Ω

The control fuzzy rules of WECS are presented in Table 4. CL, CM and CH are input currents, VL, VM and VH are the input voltages and output duty ratio are mdL, mdM and mdH.

Table 4: Control Fuzzy Rules for the WECS

	CL	CM	CH
VL	mdH	mdH	mdM
VM	mdH	mdM	mdM
VH	mdM	mdM	mdL

3.3 Energy Management System(EMS)

The control algorithm is established based on power balance theory. Figure 13 is the simulation block of the Energy Management System.

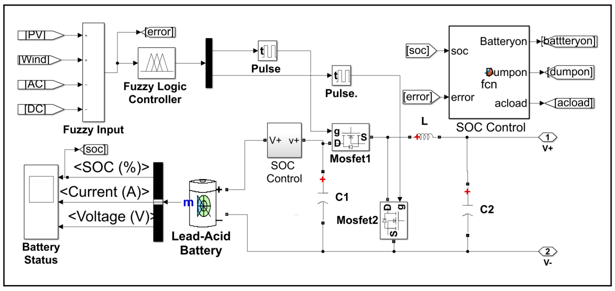

Figure 13: Energy Management System

Battery and Bi-directional converter specification is shown in Table 5.

Table 5: EMS Parameters

Parameter	Value	Unit
Nominal Voltage	48	Volts
Rated Capacity	100	Ah
Initial SOC	60	%
Battery Response time	0.01	Sec
Inductance	1	mH
Capacitance	85	μF

3.4 Integration of SECS-WECS-EMS with AC and DC Loads

The SECS-WECS-EMS are integrated with the ac and dc loads as shown in Figure 14.Figure 15 shows the solar irradiance and wind speed levels used in this system.Figure 16 shows the combined power of PV-wind which is around 540 watts at MPP.

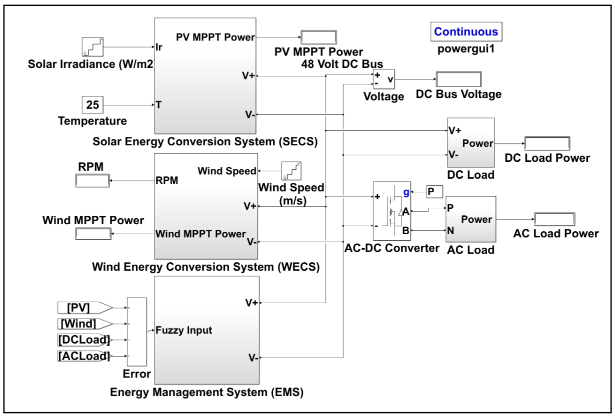

Figure 14: Integration of Hybrid System

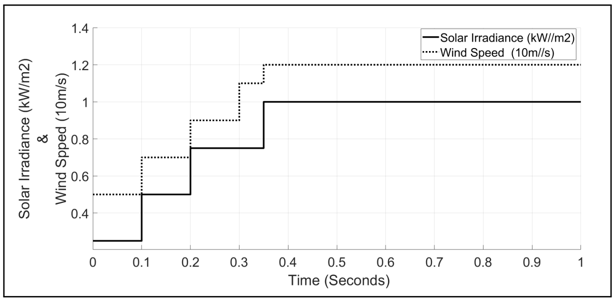

Figure 15: Solar Irradiance and Wind Speed Levels

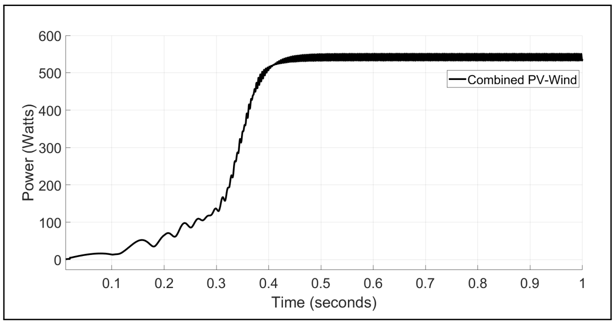

Figure 16: Combined PV-Wind Power

The EMS's Fuzzy Logic Controller is responsible for determining whether the converter is operating in buck or boost mode.The error is the difference of generated power and the load power which are the inputs to fuzzy logic controller.Depending upon the error values, the operation of the bi-directional converter is obtained, either charging or discharging.

Figure 17 shows the discharging and charging mode of bi-directional converter according to the power generated and power consumed. At 0.334 seconds the power generated and power consumed are equal(error is zero) so this point is the breakeven point between charging and discharging of battery.

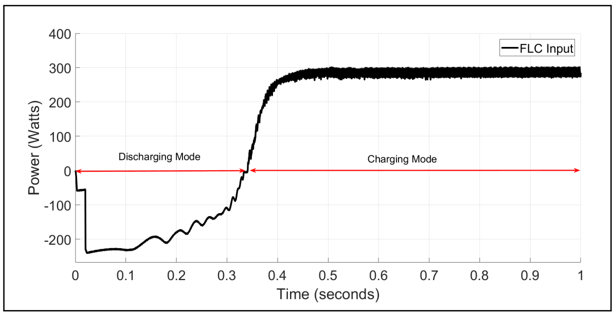

Figure 17: EMS FLC Input

The battery is initially has State of Charge(SOC) of 60 %. Initially, when the generation is less and power consumption is more, the battery starts to supply power to the loads and SOC level starts to decrease till 59.9988% at 0.334 seconds and again starts to increase as generation is more than the load consumed as we can see in the Figure 18.

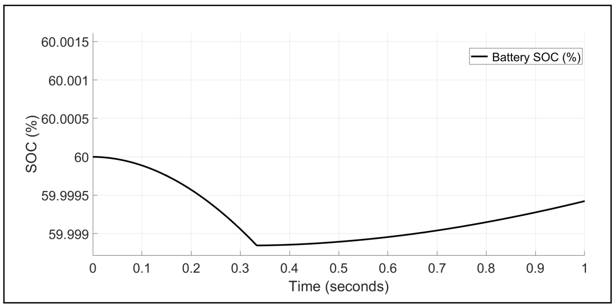

Figure 18: SOC level of Battery

The Lead-Acid battery has the nominal voltage level of 48 volts.As the battery stars supplying power to the load, the voltage level of battery stars decreasing till 47.5 volts at 0.334 seconds and again starts to increase when the battery is in charging mode due to increased generation as shown in Figure 19

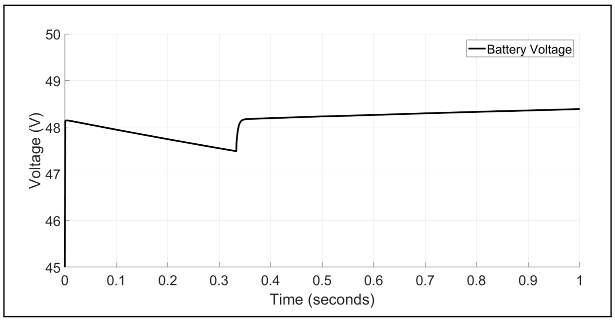

Figure 19: Battery Voltage

As there is transition of system battery from discharging mode to charging mode over the period of time,the DC bus voltage remains constant around i.e 48 volts over the period of time. There is small change of voltage level of system at 0.334 sec but is within the limit as in Figure 20.

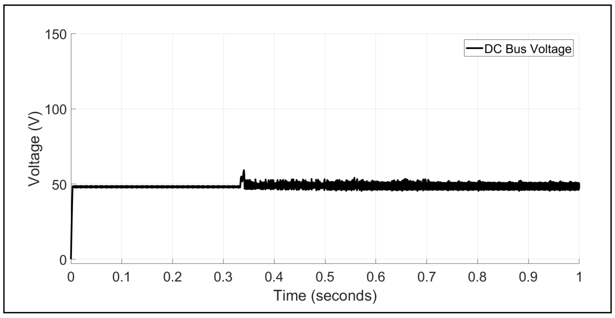

Figure 20: DC Bus Voltage

The constant 400 watts (mean value of 190 watts) ac load and dc load of 60 watts are taken as the loads for the standalone system as seen in the Figure 21. The ac loads are supplied from the inverter and dc load is connected with the DC bus directly. The dc loads has high priority than the ac loads.

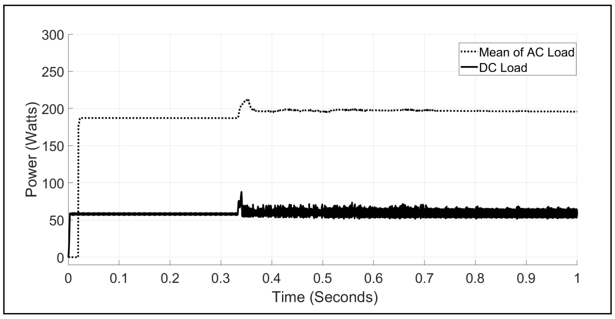

Figure 21: AC and DC Loads

4. Conclusion

In this paper, a small sized Hybrid PV-Wind-Battery renewable energy based standalone with Energy Management System (EMS) is designed, simulated and analyzed.The suggested EMS was tested using MATLAB/Simulink simulations for varied fluctuations of solar irradiance and wind speed in PV-Wind energy sources with constant load (ac and dc) demand. The MPPT of PV which is 60 Watts and MPPT of Wind which is 480 Watts were achieved using the Fuzzy Logic Controllers (FLC).FLC was also used to implement the Energy Management System (EMS) and control algorithms.The simulation graphs and waveform results show that the system is adaptable and can tolerate a wide range of PV-Wind source fluctuations. This paper allows the future case scenarios for research in fields of renewable energy.

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