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Modeling and Power Management of a Remote Stand Alone PV-Wind Hybrid System

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***Abstract*— The main focus of this study is to design a novel stand alone PV-wind hybrid energy system for remote locations where grid extension is not feasible or is expensive. The hybrid PV-wind stand alone energy system shows higher reliability compared to wind or PV stand alone systems as wind and solar technologies complement each other. A Matlab/Simulink model of an integrated stand alone PV-wind hybrid system using a battery for storage and backup protection is presented. The individual components of the system are discussed and modeled. A novel and unique control strategy is designed and simulated to control the power flow of the system while maintaining the battery charging and discharging limit. In addition, different converter design and maximum power point tracking control are applied to ensure efficient and reliable power supply under various atmospheric and loading conditions**.

Keywords **— Hybrid Energy, Stand Alone System, Photovoltaic, Wind Energy, Power Management, Matlab/Simulink and Control.**

I. INTRODUCTION

Due to the continuous increase in energy demand associated with growing environmental protection awareness, alternative or renewable energy sources have drawn great attention worldwide such as solar and wind energy which are widely used in various geographical locations. These two types of energy sources are considered most preferable renewable energy sources due to their availability and inexhaustibility [1]. However, due to the intermittent nature of solar radiation and wind speed, independent photovoltaic (PV) or wind turbines generator (WTG) alone cannot provide reliable power supply [2]. To solve this limitation, previous researches were conducted using back-up diesel generator (DG) or large storage system for consistent operation. However this can be further enhanced by introducing a hybrid connection of PV and wind energy systems with storage device being the key solution for stand alone applications [3-10].

Moreover, based on several economic analysis PV-wind and PV-wind-diesel hybrid energy system with or without battery backup are now considered cost effective technologies for electricity generation as stated in many studies [11-15]. Most of these previous studies are mainly proposing different ideas for optimum sizing of the different component of the hybrid system, various control strategies for power converter and economic analysis of the hybrid system. Besides these, stand alone hybrid system reliability issue is vital for continuous power supply under any weather condition. In addition, battery charging and discharging limit control and battery bank efficiency maintenance are also very important.

In literature few studies were conducted on power management of the renewable energy hybrid system where system efficiency, power fluctuation smoothing, hydrogen generation and hybrid power system containing ultra capacitor bank were considered [16-20]. In these studies, PV-wind hybrid energy system modeling with a new power management strategy has not been fully investigated. Therefore, this paper discusses a unique power management strategy that enhances the hybrid system performance by introducing battery charging and discharging limit control, load priority setting and secondary load control. This proposed strategy has been implemented on a PV-wind hybrid energy system model with battery backup and concluded its reliability for deployment as a power system in remote location and during natural disasters.

II. PV-WIND HYBRID ENERGY SYSTEM MODEL DESCRIPTION

The proposed topology consists of a stand alone PV-wind hybrid energy system with battery storage supplying both AC and DC loads (Figure 1). This system is mainly divided into two subsystems: PV subsystem and WTG subsystem.

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The PV subsystem consists of an array of 15 modules connected in series, a MPPT (Maximum power point tracker) controller associated with a DC-DC power converter, lead-acid battery and load side DC-AC converter or inverter. The MPPT controller of the PV system is designed based on the incremental conductance method to extract the maximum power. The DC link and AC load terminal voltage of this system is controlled by the battery storage and the inverter RMS (Root mean square) based control respectively. The main purpose of this subsystem is to support the DC load first and then the AC load in case of excess energy. On the other hand, the wind energy subsystem includes a wind turbine associated with a blade pitch angle control, permanent magnet synchronous generator (PMSG), an uncontrolled diode rectifier, a wind MPPT system connected to a DC-DC power converter, battery and load side DC-AC inverter. To ensure the maximum power extraction, a conventional MPPT is designed. Similar to the PV subsystem, the DC link and AC terminal voltages are controlled by the storage device (Battery) and RMS based inverter control, respectively. However, the wind subsystem supplies the AC load only. The overall system power rating is 5kW where the PV subsystem contributes to 3kW power and the remaining 2kW power are generated by the wind conversion system. Each battery subsystem is designed to withstand one day autonomy.

The power management system composed of a battery charging and discharging at a controlled limit, AC and DC load management, secondary load (Hydrogen generation or Heater) control and load priority setting. Also highlighted various controller systems required for MPPT, PV and wind side converter and inverter to ensure power conditioning and integration of the different subsystems. In order to access the performance of the proposed hybrid system, the individual components of each subsystem are briefly described in the following section.

A. Photovoltaic System

A PV cell generates a direct current (DC) flow that is proportional to the incident light radiation through a connected load. An ideal solar cell model consists of a diode in parallel with photo current source proportional to the radiation intensity.

Practically, a shunt resistance and a series resistance are also added to the ideal model representing the internal losses of the PV cell. The most common mathematical expression for the practical PV cell current is given by [21]. This mathematical equation requires manufacturer data regarding the voltage and current value at the maximum power point and open circuit and short circuit conditions and the number of solar cells. In this study, Kyocera (KC200GT) module has been used for PV modeling (Figure 2) and the manufacturer data for this PV module is highlighted in Appendix 1.

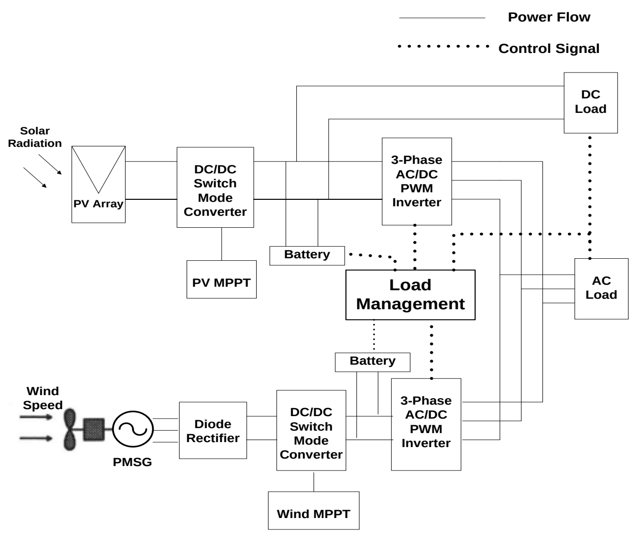
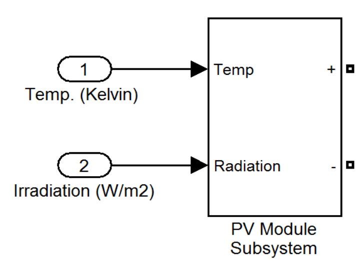


Figure 1: Schematic diagram for the proposed stand alone PV-wind hybrid energy system



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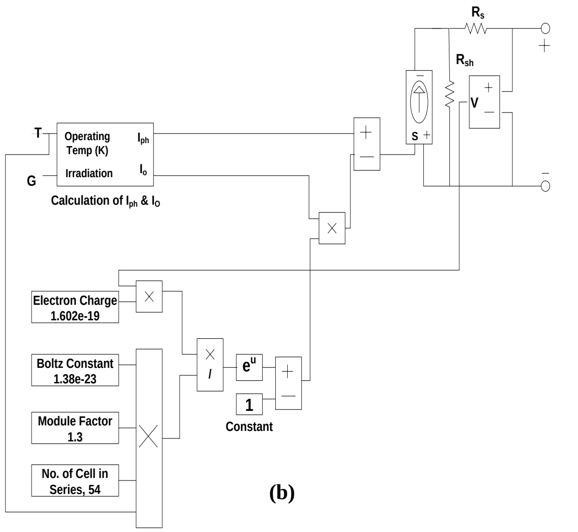

Figure 2: PV module sub system (a) inside the sub system (b) in Simulink

B. PV MPPT System

To extract the maximum power from the PV generator under different atmospheric conditions a MPPT controller is required in the system. Several MPPT algorithms such as constant reference method [22], incremental conductance method [23] and perturb and observe method [24] can be used to track the maximum power point of the PV generator. Incremental conductance algorithm is designed and implemented for MPPT operation due to its high accuracy and good tracking performance under various atmospheric characteristics [25].

C. Wind Energy System

The kinetic energy of wind is converted to electrical energy by means of wind turbines which are divided into two categories according to the types of axis around which the turbine rotates. The wind turbine that rotates around the horizontal axis is most commonly used rather than the vertical axis wind turbine. The power produced by the wind generator is proportional to the cube of the wind speed [26]. In this study a 2kW horizontal axis Hummer wind generator is considered. The parameters of the selected wind generator are given in Appendix 2.

D. Wind MPPT and Pitch Angle Control

In case of variable speed, wind turbine maximum power is extracted through conventional method where the generator speed is measured to determine the reference torque which is further used to calculate the reference DC current. The error between the reference and measured DC current is used to generate the switching pulses for the MPPT converter to regulate the output of the diode rectifier and the generator torque [26].

A pitch angle controller is deployed to maintain an optimum power under any atmospheric condition, which is accomplished by adjusting the aerodynamic torque of the wind turbine. In addition, it prevents the mechanical power from exceeding the design limit. This work describes a conventional pitch angle control strategy that is implemented by considering the generator speed as an input [27].

E. Inverter Control

Root Mean Square (RMS) based inverter control loop is implemented to adjust the AC terminal voltage of the inverter. The error generated by the measured and reference AC RMS voltage is deployed to generate the switching pulses for the PWM inverter. In order to maintain the system frequency, a discrete virtual phase lock loop (PLL) is applied [25]. However, to ensure reliability, a new power management system is designed and described below.

III. Hybrid Power Management Strategy

To operate the stand alone PV-wind hybrid energy system a customized control strategy is implemented ensuring higher reliability of this system under different atmospheric conditions. The control strategy proposed is developed based on the state of charge (SOC) of the batteries which includes AC and DC load control, secondary AC and DC load control during higher generation and most importantly the battery charge and discharge limit control. The proposed control, subdivided into five different stages, considers all possible operating conditions to run a hybrid system efficiently and reliably under different weather conditions. The block diagram representation of the suggested control strategy is shown in Figure 3. The major five control stages are:

1. Initialization
2. Normal operating condition
3. Lower limit of battery SOC control (High load or low generation)
4. Upper limit of battery SOC control (Low load or high generation)
5. wind energy extreme case control.

Initialization: When the simulation is started during the first one second, no control signals are generated due to the initialization of the hybrid system.

In the practical system, initialization takes several minutes. The proposed hybrid model is simulated in Matlab/Simulink software where some simplifications are considered, which shorten the initialization time period. Once initialization time is completed, regular system based on the proposed control system begin and the operation is presented in the following paragraphs.

Normal Operation Condition: Normal operation control is initiated when both PV battery and wind energy battery SOC are within a specified range. During this operating condition, the PV subsystem initially supports the DC load while the wind subsystem contributes power to the AC load only. Whenever low wind energy generation or low SOC of the wind subsystem battery due to high AC load requirement, the control system connects the PV subsystem to the AC load through an inverter. This operation allows the wind energy subsystem to charge the battery and share the AC load with the PV subsystem at the same time.

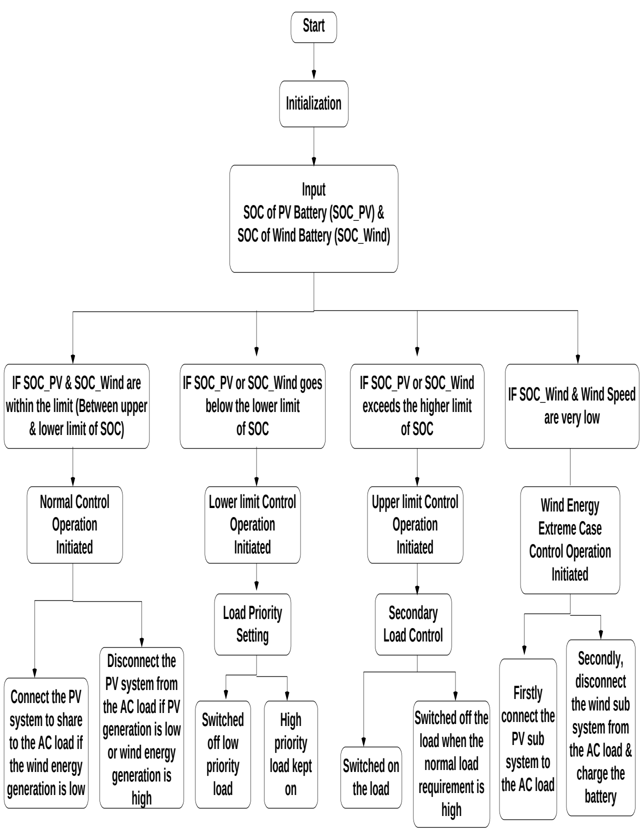

Figure 3: Block diagram representation of the proposed control strategy

While simultaneous supporting the AC and DC load at the same time, if the PV generation is lower than a certain threshold or the PV battery SOC reached its lower limit (or depth of discharge), the PV connection is switched off from the AC load in order to save the battery from deeply discharge. This is achieved while the WTG charges the corresponding battery to support the AC load alone. If the battery SOC reaches its lower limit, a constant system is needed.

Lower Limit of Battery SOC Control: Battery lower limit SOC control is initiated when the load requirement is high or the generation is low. In order to ensure battery life, the battery should be charged and discharged within a defined limit. During low generation caused by low wind speed and low radiation, the battery will first try to support the deficient load. If this condition persists for a long time, load priority is set by the control system in order to save the battery from the low level of discharge leading to the lower limit of SOC. In case of the PV subsystem, if the battery SOC reaches its lower limit, at first, the PV system is disconnected from the AC load. Secondly, if the PV battery SOC continues to decrease, the low priority DC load is switched off and only the high priority DC load is supported. Similarly, in the wind subsystem when the battery SOC reaches its lower limit at first, the PV system is connected to share the AC load and secondly, load priority is set if the SOC of the battery continues to decrease. As battery gets charged by the PV and WTG, an allowable SOC limit should be attained, hence the need for an upper SOC control limit.

Upper Limit of Battery SOC Control: Battery upper limit SOC control describes the situation when renewable energy generation is high or load demand is low. During this operating condition, secondary AC or DC loads are turned on in order to maintain the battery charge limit. Such condition is recommended as the system is stand alone and the excess energy must be dissipated. When the PV subsystem generation is high and the battery is fully charged, the controller switches on the secondary DC load. Similarly, during high wind, the AC secondary load is turned on to absorb the surplus energy left after supporting the loads and charging the battery. In case of no excess energy secondary loads are turned off accordingly.

Wind Energy Extreme Case Control: This controller application is assigned for the condition when there is low wind power generation due to less wind speed and the wind energy subsystem battery SOC is below the lower limit (below the depth of discharge).

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When such condition takes place, the controller initially switches on the PV subsystem to support the AC load and then disconnects the wind energy subsystem from the AC load when the wind battery SOC decays continuously; thus, wind power will only be used to charge the battery. When the battery is charged up to a threshold level (set by user) the wind energy subsystem is reconnected to the hybrid system and supports the AC load.

IV. Simulation Results And Discussion

The proposed stand alone PV-Wind hybrid energy system with battery storage is simulated using Matlab/Simulink, allowing a detailed performance analysis of each individual component. The Matlab/Simulink model of the system (Figure 4) represents the whole system which is divided into two subsystems: (1) PV generation and (2) wind energy generation equipped with the power conditioning devices described earlier. Each individual component of these renewable energy subsystem are modeled and its performance is evaluated. In addition, the overall performances of this hybrid system under different atmospheric and loading conditions are also analyzed and highlighted in the next section.

A. *PV Generator Output Characteristics*

Both solar radiation and temperature are considered as input parameters of the PV generator, where both of them are changing randomly. Solar radiation ranged from 0 to 1000W/m^2 while temperature is changing around 25^{0}C. Moreover, the MPPT system combined with DC-DC converter is also modeled. The performance analysis of the PV generator is presented in Figure 5 where the characteristics curve of the PV array under various solar radiation are highlighted as well as the corresponding PV generator power and PV voltage and current. From Figure 5, it can be noted that in order to extract the maximum power at different radiation, the PV array current shown in Figure 5(f) is changing while the PV voltage illustrated in Figure 5(e) is almost fixed at 400V which is the maximum power point voltage depicted in Figure 5(b). The same characteristic is also observed in Figure 5 (a and b) where the maximum power point value is 2082W at 700W/m^2, 2403W at 800W/m^2, 2727W at 900W/m^2 and 3054W at 1000W/m^2 for different solar radiation are similar to the generated power values in Figure 5(d) justifying the operation of the designed MPPT controller.

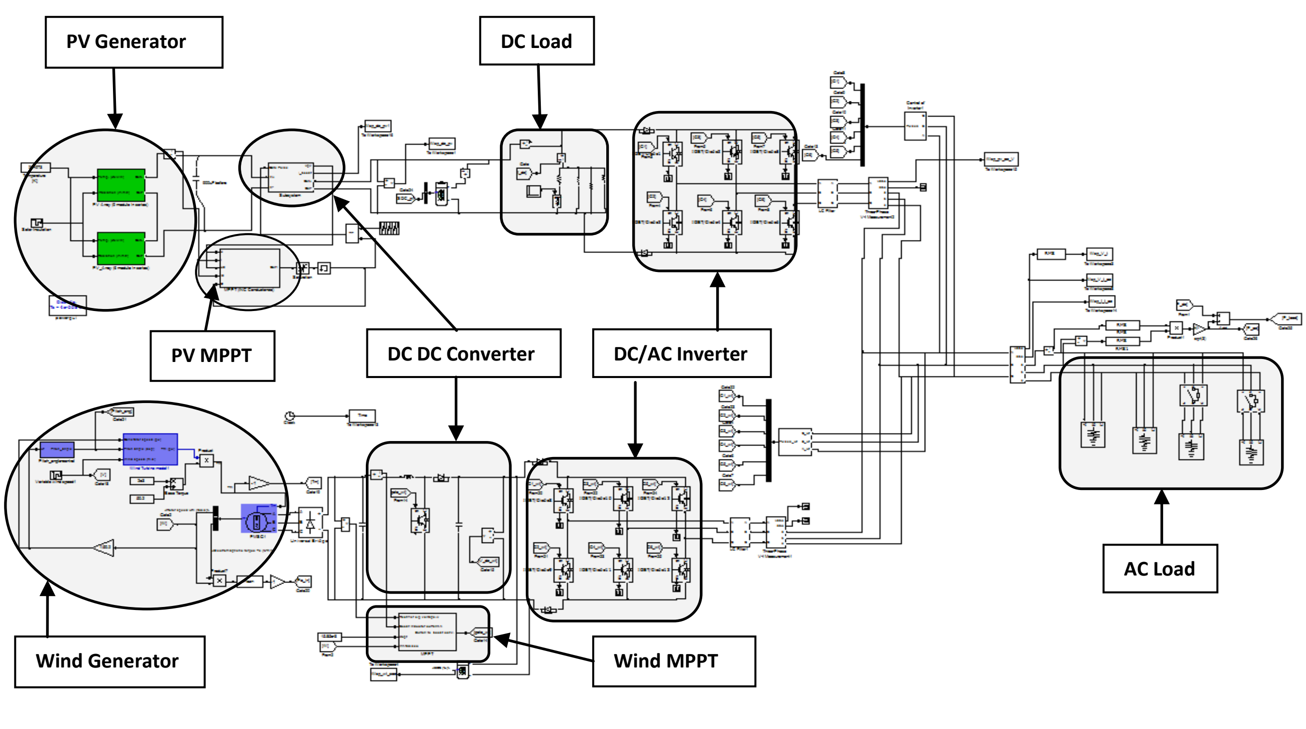

Figure 4: Matlab/Simulink model of PV-Wind hybrid energy system

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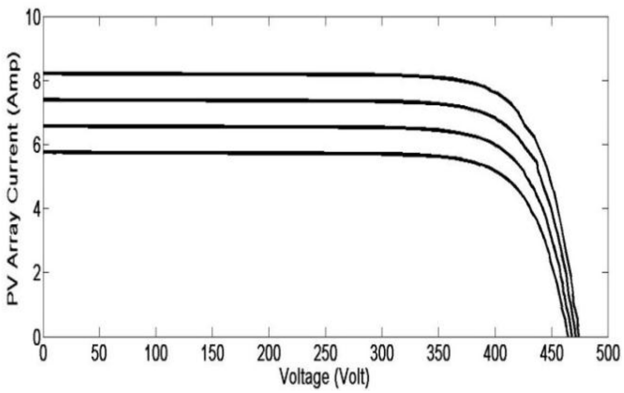

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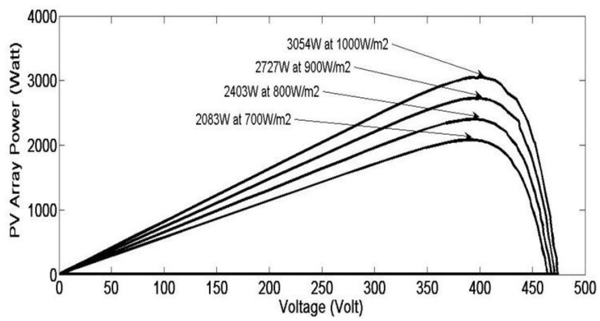

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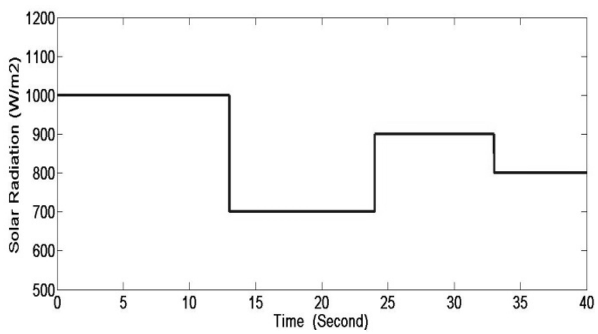

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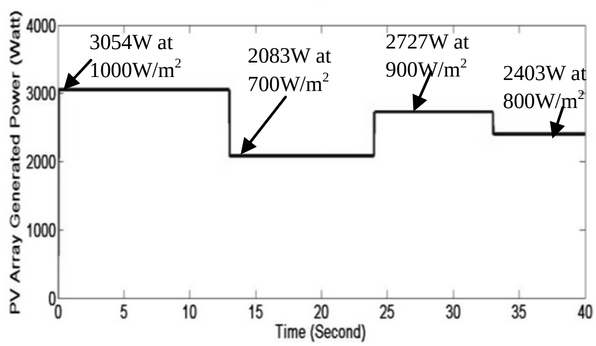

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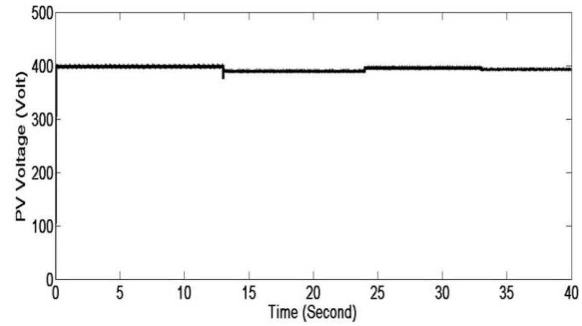

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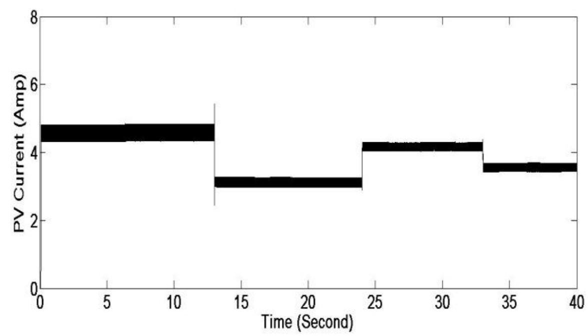

(f)

Figure 5: PV (a) I-V characteristics, (b) P-V characteristics, (c) different solar radiation, (d) PV generated power, (e) PV voltage and (f) current

B. Wind Generator Output Characteristics

The main components of the wind generator consisted of wind turbine, pitch angle controller, wind energy generator (PMSG), uncontrolled diode rectifier, DC-DC power converter associated with wind MPPT system. For the wind turbine subsystem, wind speed and pitch angle are considered as inputs where wind speed is randomly varied. Based on the simulation output (wind speed, generator speed and torque and the output power) of the wind generator subsystem (Figure 6) is observed that the generator torque must also vary with the wind speed according to the MPPT to maximize the output power of wind generator under different atmospheric conditions. To check the MPPT design validity, it is necessary to calculate the ratio of initial torque (40Nm) to final torque (18Nm) and also the ratio of the initial (9m/s) and final (6m/s) wind speeds. As the ratio of torque (2.23) is almost equal to the square of the wind speed ratio (2.25), it can be concluded that the wind system is following the maximum power point.

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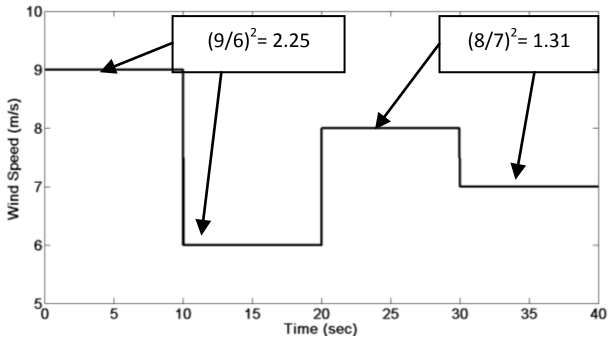

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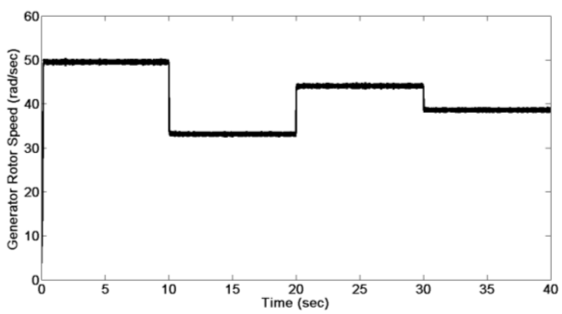

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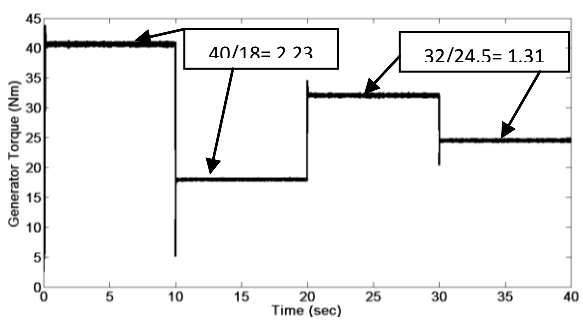

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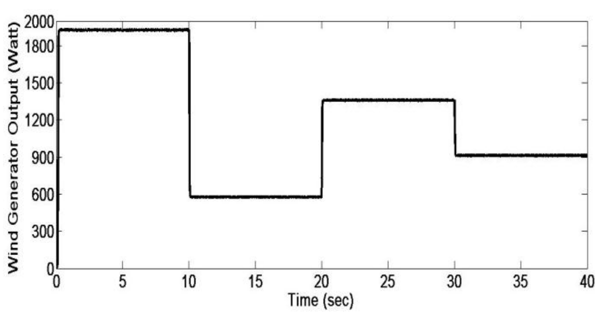

(d)

Figure 6: Wind generator output characteristics (a) wind speed, (b) generator rotor speed, (c) generator torque, (d) generator output power

C. Wind Hybrid System Output Characteristics

The individual systems described in the earlier sections are combined together to build the hybrid model in addition to the battery storage system used to enhance the system stability. The proposed stand alone hybrid model is supplying simultaneously both AC and DC loads. To analyze the performance of this stand alone PV-wind hybrid system, two operating conditions are considered:-

1. both solar radiation and wind speed were fixed
2. both solar radiation and wind speed were varied

The performance of the hybrid energy system is analyzed based on the proposed power management control system described in the previous section. Each subsystem is supported by one lead-acid battery capable of supporting the load for one day with no sun and wind. The upper and lower SOC limits for the PV subsystem battery and wind subsystem battery are considered to be 80.006 (Upper limit) and 79.9851(Lower limit) and 80.006 (Upper limit) and 79.9750 (Lower limit) respectively. Practically, the upper and lower limits of the battery SOC are set at 80% and 20% respectively [26]. The chosen SOC ranges used in this work is due to the lack of availability of high configuration desktop computer. In order to have practical lower SOC limit of 20 (most commonly 20% depth of discharge is used) for both systems, extended memory space is required to simulate the system for extended duration. With 40sec simulation run time at selected lower and upper SOC limits, were selected around 32 million data are generated, covering almost the entire space of the random access memory (RAM). Due to this limitation all the presented data are results of 40sec simulation at described SOC limits. The simulation results for each operating condition are described below.

Both solar radiation and wind speed are fixed: During this operating condition, both solar radiation and wind speed are fixed at a rated value (1000W/m^2 and 9m/s) where maximum power is generated from both renewable energy subsystems. Under such condition, both AC and DC loads are varied to verify the designed control strategy supporting the loads with optimum combination of renewable energy sources and battery. In addition, it also prevents the battery from overcharging or deeply discharging. The simulation results for this operation condition are presented in Figure 7. The generated power shown in Figure 7 (c and d) is the output power of the DC-DC power converter. The efficiency of the PV and wind subsystem DC-DC converter is calculated to be 97% and 95%, respectively.

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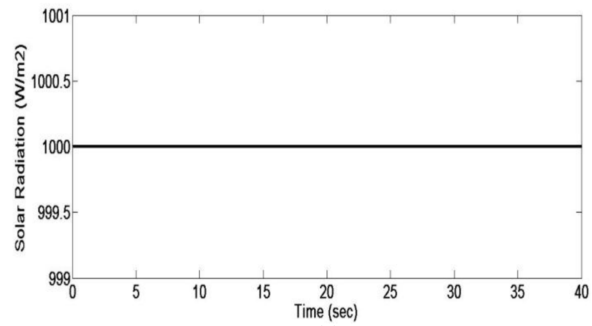
Different loading conditions (both AC and DC load) under rated power generation are also shown in Figure 7 (e and f). During the simulation the battery charging and discharging power is depicted in Figure 7 (g and h) where positive power describes discharging phenomenon and negative power implies charging mechanism. Additionally, PV and wind subsystems battery SOC values are noted in (Figure 7 (i and j)).

At the beginning of the simulation, the PV system supports the DC load while the wind energy system supports the AC load only. As the AC load demand increases beyond generated value, the SOC of the wind battery decreases while the PV battery SOC increases due to low load demand compared to generation. This decreasing and increasing rate of battery SOC is continued up to 5sec. At around 6sec, PV battery SOC reaches its upper limit and hence, based on the control design, the PV subsystem is connected to the AC load forcing the PV battery SOC to start decreasing without the need to switch on secondary loads. At 13sec, another control operation is achieved due to reaching the lower SOC value of the PV battery. As the PV subsystem supports both AC and DC load, the battery SOC continues to decrease and attains its lower SOC limit. During this condition, the controller initially disconnects the PV subsystem from the AC load. It then switches off some low priority DC load (Figure 7f) as the overall DC load demand exceeds the PV power generation causing the PV and wind system battery SOC to increase and decrease respectively. The next controller operation is observed between (17 to 18)sec when the wind subsystem battery SOC reaches its lower limit. During this time period the PV subsystem is reconnected in order to share the AC load. In doing so, the wind system battery SOC starts increasing but suddenly it starts decreasing due to the AC load increase in the system. In order to save the wind system battery from deeply discharging the controller turns off some low priority AC loads resulting in the wind battery charging while supporting the high priority AC loads. The secondary load control operation is initiated at around 20.5sec when the PV battery SOC exceeds its upper limit. At such states, at first the controller checks whether the PV subsystem is connected to the AC load or not. If so, the controller switches on the secondary DC load to save the battery from over charging. This secondary load is supplied by the PV subsystem until the battery SOC reduces to a certain level or any other new load is connected to the system. From Figure 7 (f and i), it is noted that the secondary DC load is on at 20.5sec and off at 24sec.

This DC secondary load operation is then repeated during the time period of (26 to 40)sec as there is no regular load change in the system. In the case of wind energy subsystem, the AC secondary load operation is initiated at around 28.5sec. When the wind system battery's SOC is at its upper limit, the controller disconnects the PV subsystem from the AC load in order to discharge the battery but even after the battery SOC continues to escalate, the secondary AC load turns on to save the battery from over charging as shown in Figure 7 (e and j). The switching off operation of this AC secondary load is similar to the DC secondary load switched off operation. This operation is repeated during the time period of (31 to 40)sec, except when the battery SOC value is within the limit, no control signal is generated.



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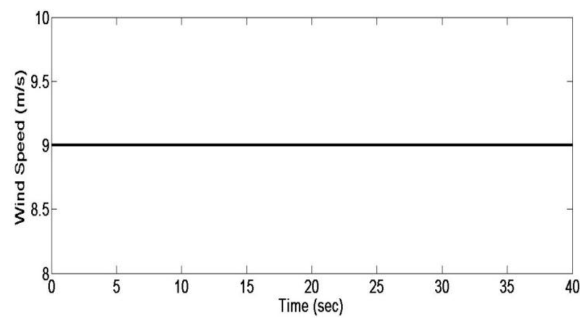

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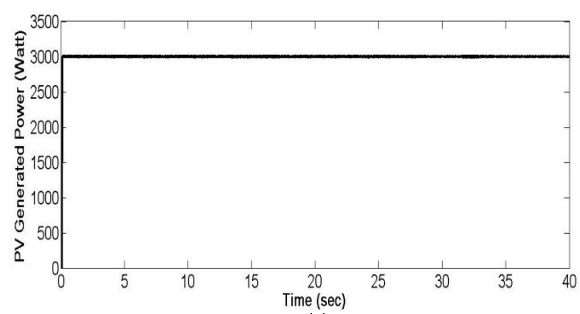

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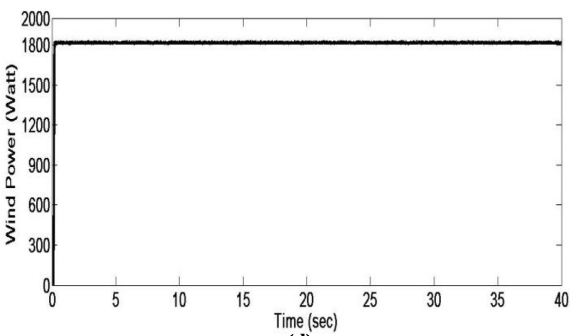

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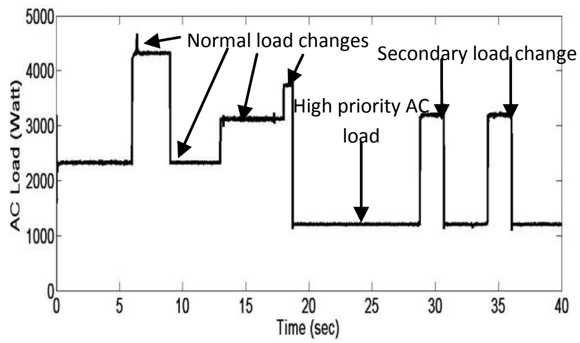

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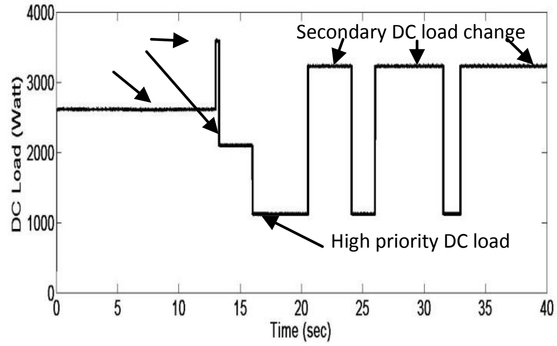

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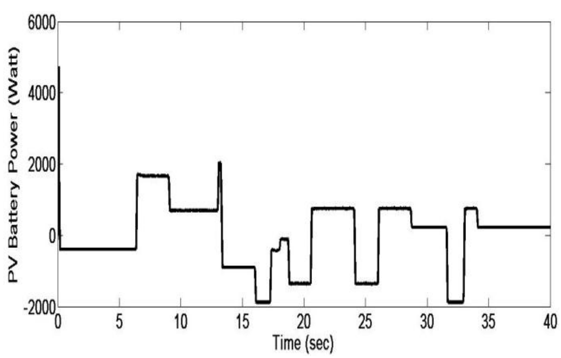

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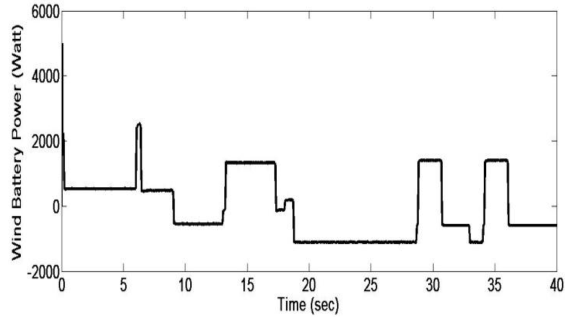

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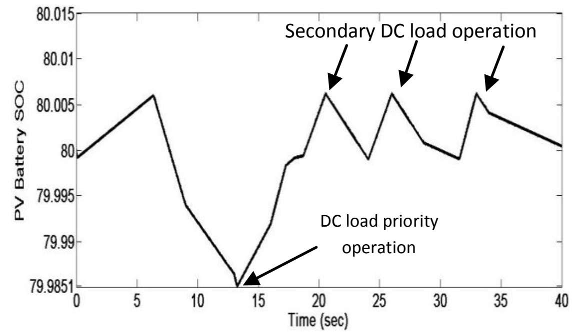
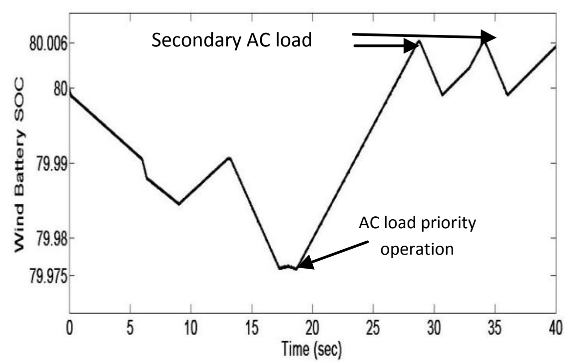


(i)

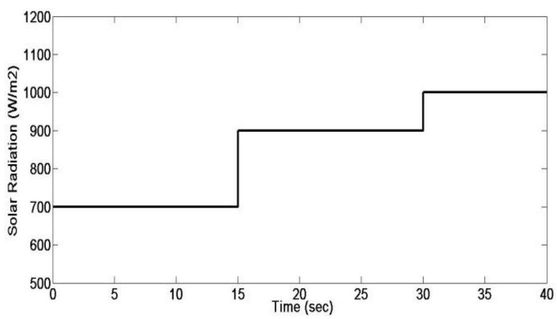


(j)

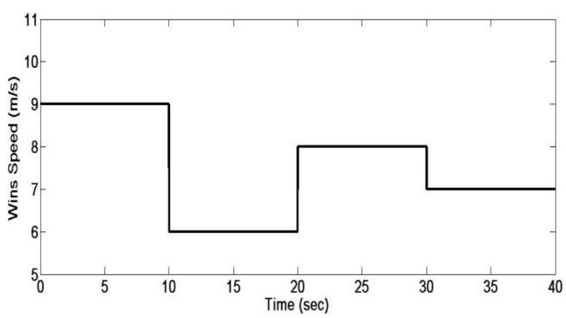
Figure 7: Performance analysis of constant solar radiation and wind speed

Both solar radiation and wind speed were varied: The same system is repeatedly tested under variable solar radiation (day part) and wind speed. Figure 8 highlights the results showing the correct operation of the control system where the batteries are performing based on the design. The simulation results for this operating condition are illustrated in Figure 8.

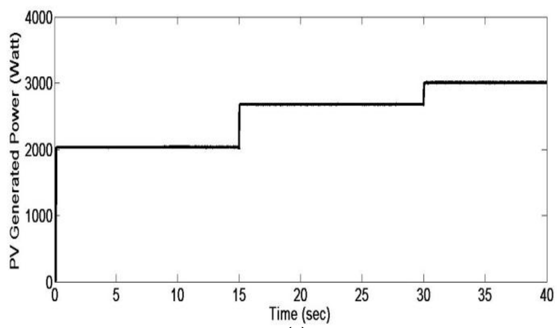
The variation in solar radiation and wind speed are shown in Figure 8 (a and b), while the generated power from PV and wind subsystem are presented in Figure 8 (c and d), AC and DC load variations are illustrated in Figure 8 (e and f) and the PV and wind subsystem battery charging and discharging power are depicted in Figure 8 (g and h) leaving the SOC to be shown in Figure 8 (i and j). In this operating condition the wind energy extreme case control operation is observed along with the other control operation which is described in the previous condition. During the time period of (12.5 to 19.5)sec the controller initiates the wind energy extreme case control due to the low battery SOC (Figure 8j) and wind power generation (Figure 8c). Because of this control operation, the wind subsystem is disconnected from the AC load and charges the battery. Once the battery charges up to a threshold level the controller reconnects the wind subsystem to the AC load.



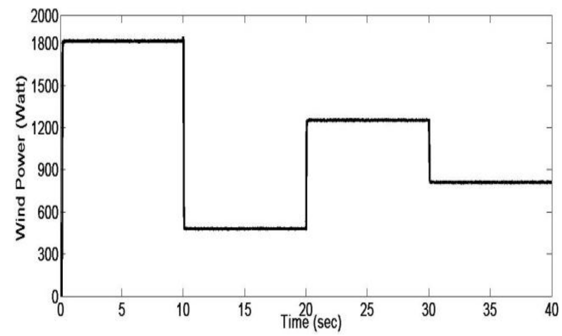
(a)



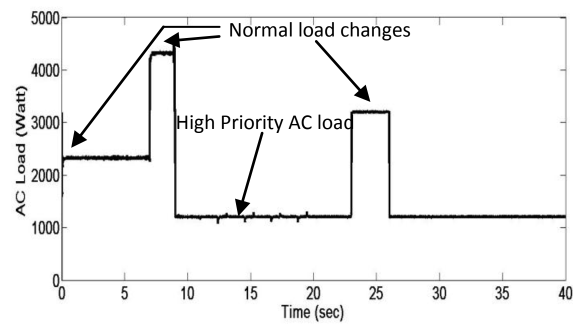
(b)



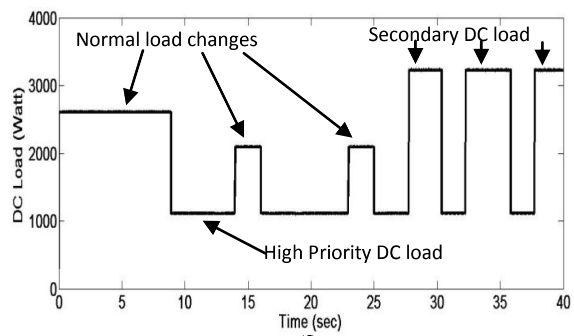
(c)



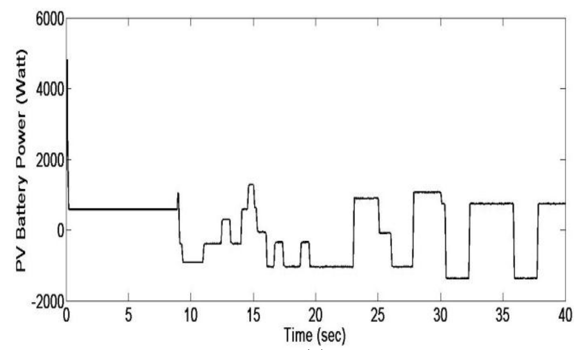
(d)



(e)



(f)



(g)

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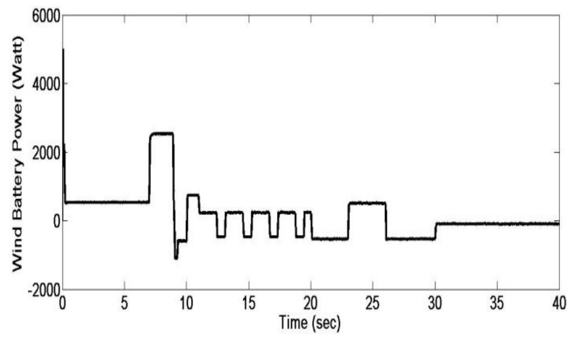
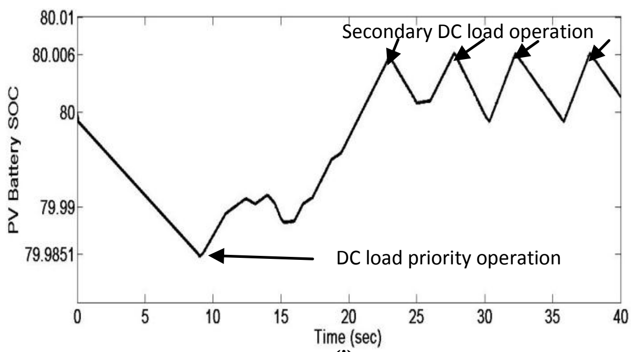
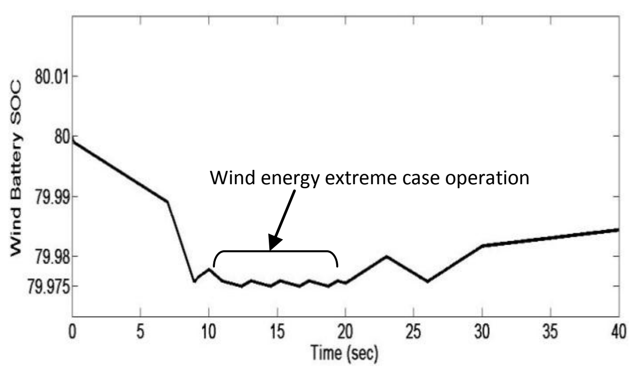


(h)



(i)

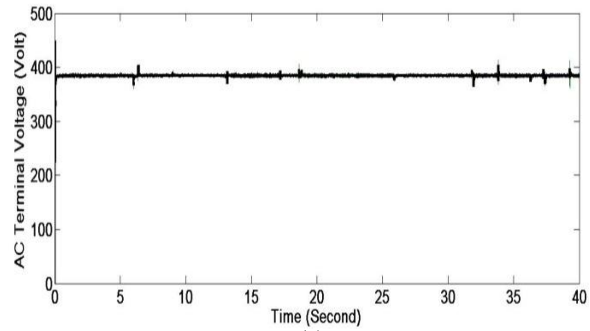


(j)

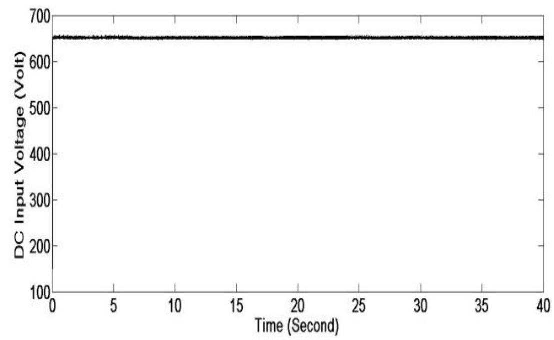
Figure 8: Performance analysis of variable solar radiation and wind speed condition

In addition to the conditions shown in Figure 7 and 8, there are two voltage control actions, the first one related to the AC terminal voltage control and the second one is linked to the DC link voltage control. In both operating conditions these two controllers maintain an AC terminal voltage and a DC link voltage fixed at 385V (RMS) and 650V respectively.

Figure 9 (a and b) expresses graphically that both targets are achieved with high stability, although there are some variation in load, wind speed and solar radiation.



(a)



(b)

Figure 9: Voltage control (a) AC terminal voltage and (b) DC link voltage

V. CONCLUSION

This paper presents the performance analysis of a novel PV-wind hybrid energy power system with battery storage under various atmospheric and loading conditions. A detailed modeling of both PV and wind subsystem components are discussed and simulated in the Matlab/Simulink environment. The novel hybrid power management strategy is developed to control the power flow of the system and maintain battery charging and discharging limits under any operating conditions. Two different operating conditions are highlighted showing the validation of the control system designed. Based on the results shown, the following conclusions have been drawn.

1. Reliability of this hybrid model is enhanced by the proposed power management technique.
2. Battery charging and discharging limits control are achieved.

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3. Dynamic behaviors of this hybrid model are accomplished under different solar radiation and wind speed conditions.
4. The proposed hybrid system performs well under different loading conditions.
5. Both AC and DC loads are supplied by this hybrid model under any atmospheric condition.
6. Modeling of different controller (MPPT system, DC-DC power converter, DC-AC power converter) ensure efficient and high quality power supply to the load.

Based on the above analysis, it can be concluded that the proposed hybrid scheme offers a reliable and alternative solution of renewable energy to meet the increasing power demand, overcoming any intermitting challenges and allowing widespread development of such systems especially in locations where no grid is available.

VI. APPENDICES

APPENDIX 1:

Table 1:
Kyocera KC200GT PV module parameters

Parameters	Values
V_{oc}	32.9V
I_{sc}	8.21A
V_{max_power}	26.32V
I_{max_power}	7.61A
P_{max_power}	200.143W
No of Cell in Series	54

APPENDIX 2:

Table 2:
Wind turbine and generator parameter

Wind Turbine	
Blade Swept Area	$3.8m^2$
Air Density	$1.225\ kg/m^2$
Base Wind Speed	9m/s
PMSW	
No. of Poles	6
Generator Rotor Speed	50 rad/sec
Armature Resistance	0.5 Ω
Flux Linkage	0.51 Wb
Stator Inductance	0.008H
Rated Torque	40Nm
Rated Power	2kW

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