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Energy Management of a Renewable Hybrid Isolated DC Microgrid

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Abstract: Hybrid microgrid is the key solution to energize remote rural areas. The microgrid system incorporates more than one Distributed Renewable Energy (DRE) source to complement one another. This paper proposes a hybrid DC microgrid system to be operated in isolated mode. The proposed microgrid consists of a PMSG based Wind Turbine, PV array, and Lead-acid battery as an energy storage device. The Wind Turbine generator is connected to the DC bus through a Three-phase Diode Bridge Rectifier. The PV array is tied to the DC bus by a Boost converter and incremental conductance algorithm is used to extract the maximum power from the PV array. The battery uses a bidirectional converter for charging and discharging. A simple PI-based closed-loop control system is incorporated for proper energy management. The bus voltage is maintained either by the boost converter or the bidirectional converter depending upon the operating condition. The proposed microgrid system is modeled in MATLAB/SIMULINK software. Simulation of this model is done for varying irradiance, temperature, wind condition, and different load condition. The simulation results show that the system is stable under various load and supply conditions.

Keywords: Hybrid microgrid, Distributed Renewable Energy (DRE), PMSG, PV array, DC bus, Boost converter, incremental conductance, bidirectional converter

I. INTRODUCTION

Energy has become a part and parcel of our daily life. At every stage of our life, we are dependent on energy one way or another. There are different kinds of energy around us. Electrical energy is the most convenient form of them. It can be converted into any other form with greater flexibility. The socio-economic condition and the poverty largely depend on electricity. The supply of electricity has a great impact on the economy of a country [1]. The use of fossil fuel to produce electrical energy produces extensive CO_2 and the reserve of fossil fuel is limited [2]. So, electricity generation from renewable energy sources such as solar energy & wind energy is expanding vastly every year [3]. In many rural areas of developing countries as well as some urban slums and peri-urban areas, connections to central electric grids are economically prohibitive and may take decades to materialize. The most suitable option to provide electricity to these areas is the use of an isolated microgrid. It includes the applicability to small and remote communities and urban areas, reduced transmission and distribution losses, the allowance for direct and local private investment, local employment, and increased security of supply, as well as, in some cases, improvements in reliability, speed of deployment, local spill-over costs and reduced environmental burdens.

These isolated microgrids (MG) consist of various types of micro-generators (wind turbine, photovoltaic (PV) array, diesel generator, and wave generator), local storage elements (capacitors, flywheel), and loads. PV array which needs direct current (DC)/alternating current (AC) inverter interface or an asynchronous wind turbine which requires AC–DC–AC inversion for proper grid connection. Similarly, the storage devices used in the system may or may not require an inverter interface as in the case of capacitor banks and flywheel, respectively. A microgrid can be a DC, AC, or even a high-frequency AC grid. It can be a single or a three-phase system or it may be connected to low voltage or medium power distribution networks. Furthermore, a microgrid could be operating in either grid-connected or islanded operation mode. For each operating mode, operational requirements are different and distinct control schemes are required [4]. With regard to traditional AC, DC microgrid has proved to offer more efficient and reliable energy transfer. Calling on to this and other benefits, such as circumvention of problems with harmonics, unbalances, synchronization, and reactive power flows, different types of DC power distribution systems are experiencing more and more widespread use [5]. In this paper, a renewable hybrid isolated DC microgrid is proposed. It comprises a Permanent magnet synchronous generator (PMSG) based wind energy conversion system (WESC) and a PV array as the renewable energy sources. A three-phase bridge converter is incorporated to obtain DC voltage and the incremental conductance MPPT technique is incorporated to extract maximum power from the PV array. A battery with a proper charge controller is connected to the dc bus. The controller charges the battery when the generation is higher than the load and discharges the battery when the generation is lower than the load. The dynamic performances of the proposed DC microgrid have been demonstrated by simulations using MATLAB/Simulink environment.

II. OVERVIEW OF MICROGRID ARCHITECTURE

The simplified scheme of the considered isolated DC microgrid (MG) is depicted in Fig.1. The considered MG consists of these subsystems (1) Solar Energy Conversion System (SECS) (2) Wind Energy Conversion System (WESC) (3) battery system (4) variable load system with DC grid. The power electronic converters are used in these subsystems to ensure the smooth power transfer among load, battery, and energy conversion systems. The battery system acts as storage when the generation surpluses the demand and supplies additional energy when the generation is less than the demand. Each subsystem is modeled in the MATLAB/Simulink software, as described in the following sections.

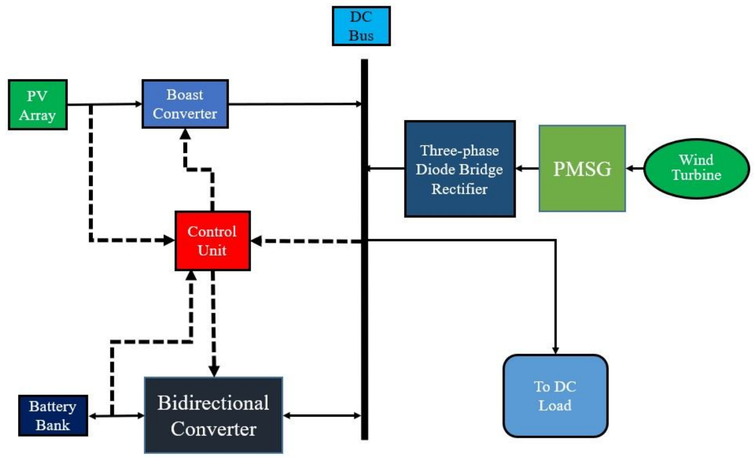

Fig. 1 Simplified configuration of the considered isolated DC microgrid.

A. *Solar Energy Conversion System (SECS)*

A single silicon solar cell can be modeled using the combination of current source, diode, and resistors [6]. Fig. 2 shows the Simulink model of the proposed SECS. The SECS includes a PV array and a boost converter. The boost converter increases the

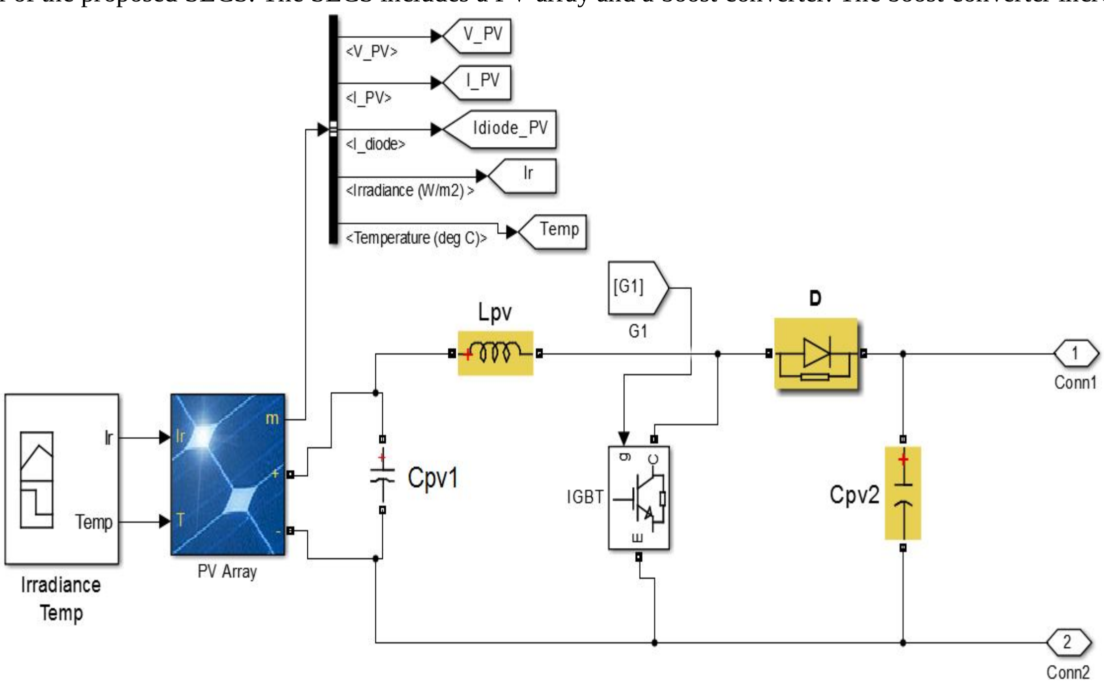

Fig. 2 Simulink model of the proposed SECS.

PV array terminal voltage to the DC bus voltage and extract the maximum power when required. Incremental conductance algorithm [3] is used to track the maximum power point (MPP). The SECS parameters used in this study are listed in Table I and Table II. Capacitor Cpv2 works as the Dc link capacitor to maintain the DC grid voltage.

TABLE I
PV array parameters

Number of parallel strings	15
Number of parallel strings	3
Single module characteristics	
Cell per module	60
Open circuit Voltage (Voc)	38.3 V
Short circuit current (Isc)	8.81 A
Voltage at maximum power point (V_{mpp})	30.2 V
Current at maximum power point (I_{mpp})	8.06 A
Maximum power (W)	243.412 W
Temperature coefficient of Voc (%/deg.C)	-0.35601
Temperature coefficient of Isc (%/deg.C)	0

TABLE II
Boost converter parameters

Array side capacitor (Cpv1)	100 µF
Inductor (Lpv)	1.6e mH
Bus side capacitor (Cpv2)	4700 µF
Switching Frequency (f)	5000 Hz

TABLE III
Wind turbine and PMSG parameters

Base wind speed	12 m/s
Max power at base speed	0.73 pu
Pitch angle	0 deg
Nominal mechanical P_{out} of WT	4.5 KW
Base power of PMSG	4.5/0.9 VA

B. Wind Energy Conversion System (WESC)

Fig. 3 shows the Simulink model of the proposed WECS.WESC consists of a variable speed gearless wind turbine (WT), PMSG, and a Three-phase Diode Bridge rectifier. The PMSG is modeled in the dq reference frame [7]. The Three-phase Diode Bridge rectifier converts three-phase AC into DC voltage. The Wind Turbine and the PMSG are modeled as mentioned in table III. At base speed, the PMSG produces 4.4 KW power at 225-volt DC.

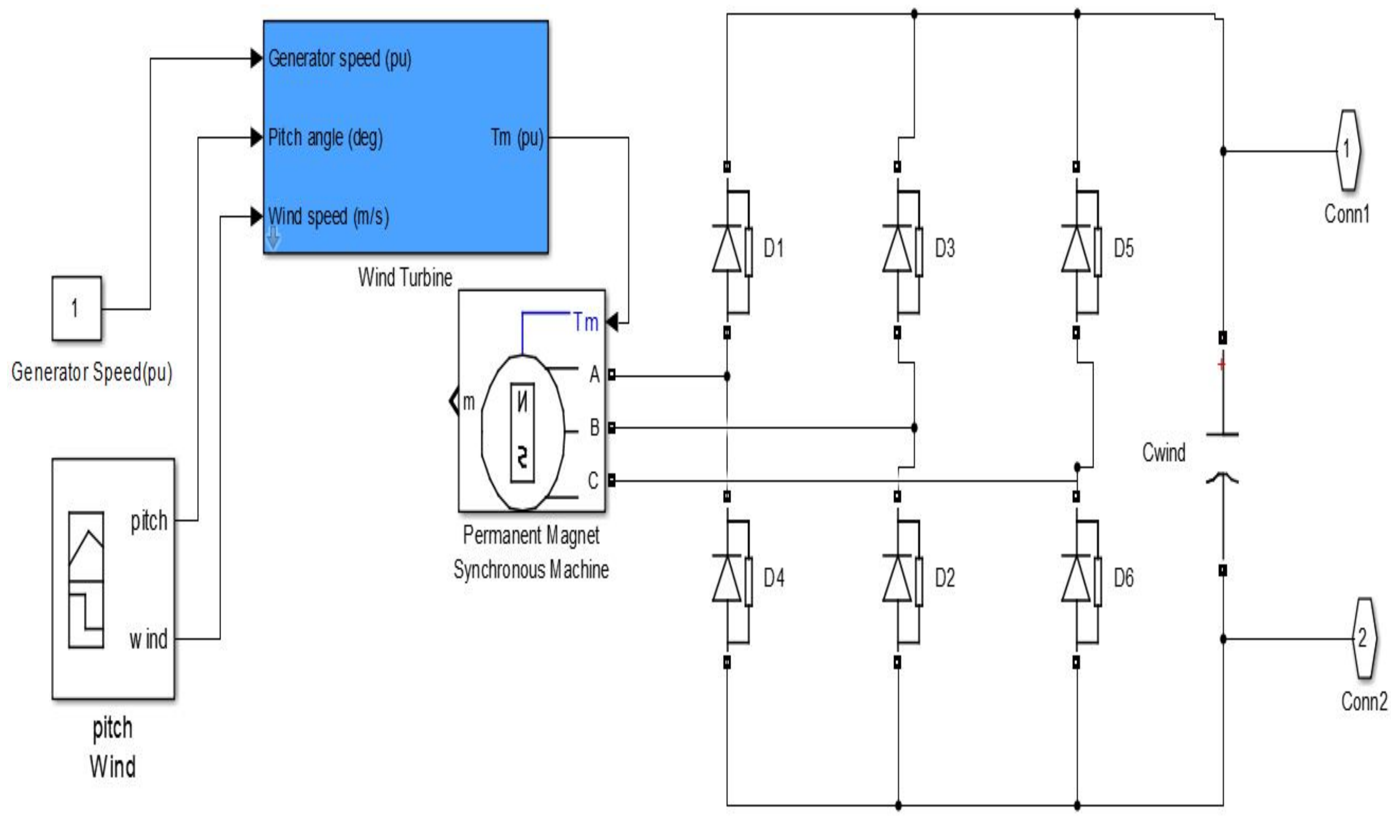

Fig.3 Simulink model of WECS

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C. Battery System

The designed Simulink battery system is represented in Fig. 4 which includes a 65 Ah Lead-acid battery and a bidirectional converter [8] for the charging and discharging of the battery. The directional converter works as either buck converter to charge the battery or boost converter to discharge the battery as required. The charging and the discharging occur in such a way as to keep the bus voltage constant. The battery system parameters used in this study are listed in Table IV.

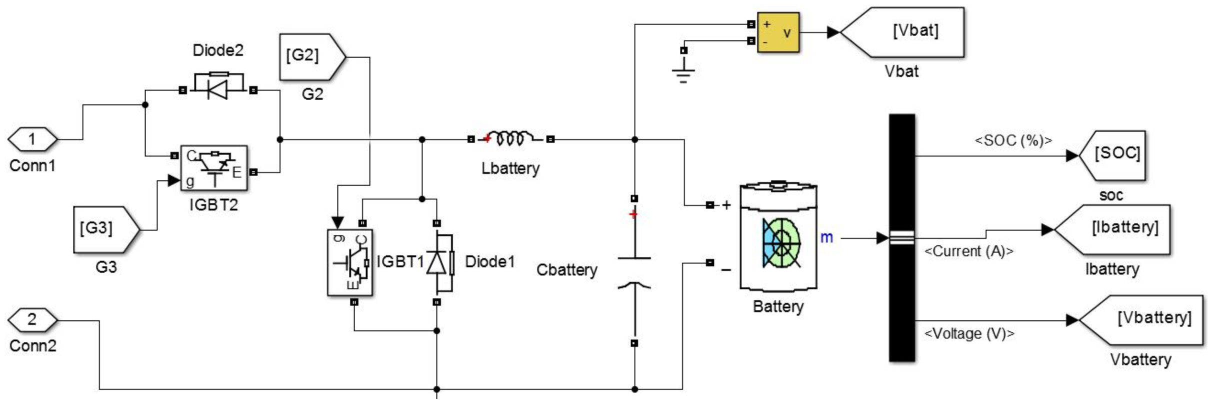

Fig. 4 Simulink model of designed Battery System

TABLE IV
Parameters of Battery System

Parameters of Lead-acid battery		Parameters of the bidirectional converter	
Nominal Voltage (V)	80 V	Inductor (Lbattery)	1.6 mH
Rated Capacity (Ah)	65 Ah	Capacitor (Cbattery)	1.6e µF
Initial State-Of-Charge (%)	50 %	Switching Frequency (f)	5000 Hz
Maximum Capacity (Ah)	70 Ah		
Fully Charged Voltage (V)	94.2373 V		
Nominal Discharge Current (A)	13 A		
Internal Resistance (Ohms)	0.012308 Ohms		
Capacity (Ah) @ Nominal Voltage	62.5		
Exponential zone [Voltage (V), Capacity (Ah)]	[86.9 13]		

D. Variable Load System with DC Grid

The proposed grid is a 225-V DC microgrid and a number of loads are connected to the grid as shown in Fig.1. The value of each load is varied for different case analyses.

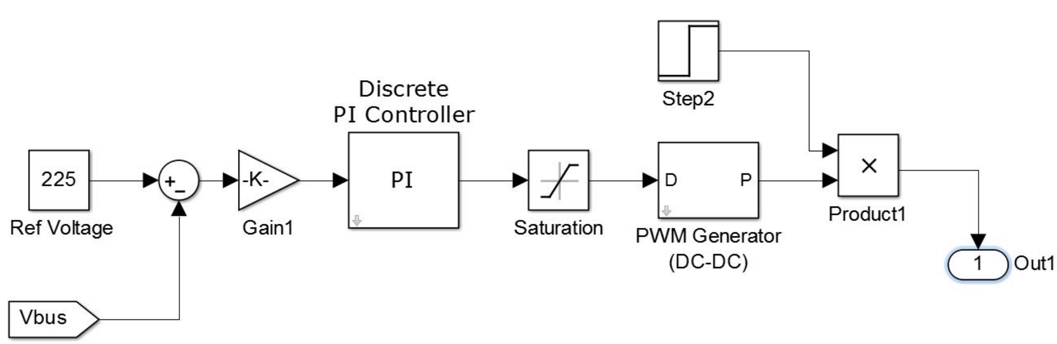

Fig. 5 Simulink model of Stable Voltage Control block

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III. CONTROL AND ENERGY MANAGEMENT STRATEGY

The system operates in such a way as to maintain the constant DC bus voltage and the proper energy management between the source and the battery storage. The WTGS does not incorporate the pitch control system, thus the only way to sacrifice the extra power to keep the energy balance, the PV array is operated in off-MPPT mode. So, a PI controller-based stable voltage Control block shown in Fig. 5 produces the gate pulse when the maximum energy need not be extracted from the PV array to maintain a stable DC bus voltage. In case of demand is greater than the generation then the battery system can provide the necessary energy to maintain the bus voltage. The energy management strategy for the different use cases is described in table V. ΔP represents the difference between the generated power from the RES and the actual demand of the load, SOC represents the state of charge of the battery.

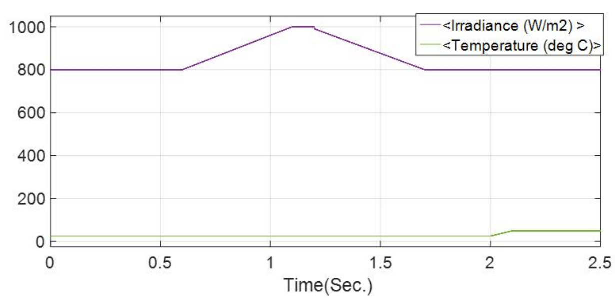
TABLE V

Condition of ΔP and SOC	Control strategy
ΔP>0, SOC>90%	The battery is in idle condition and extra power is sacrificed by operating the PV array at off-MPPT and maintaining bus voltage
ΔP>0, SOC<90%	The battery is charged at a constant current; bus voltage is maintained by PV boost converter/bidirectional Battery converter
ΔP<0, SOC>30%	Battery discharges to supply the excess load and maintains bus voltage, the PV array operates in on-MPPT mode
ΔP<0, SOC<30%	The battery is shut down and the extra load is disconnected to eliminate the mismatch between the powers

Microgrid energy management and control strategy

IV. SIMULATION RESULTS

The proposed model is simulated for various wind conditions, solar irradiance and temperature condition, load condition, and SOC condition of the battery. SECS (11 KW) and WECS (4.4 KW) are operated separately with the Battery (65 Ah, nominal voltage 80V) System during the different simulation cases for a clear understanding of the operation.



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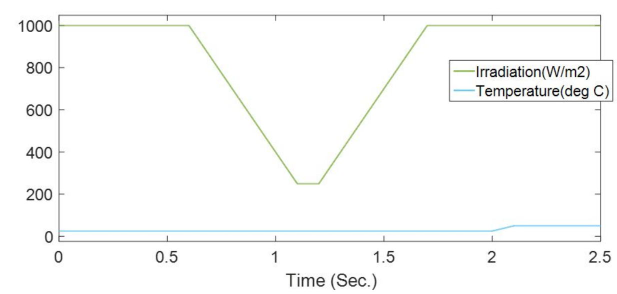

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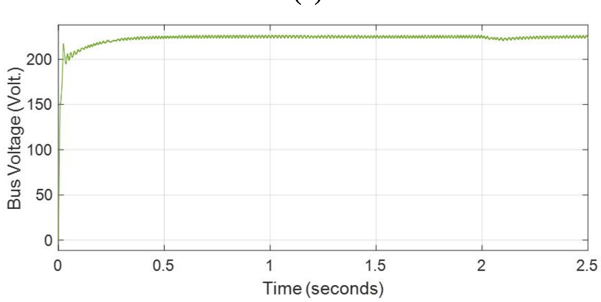

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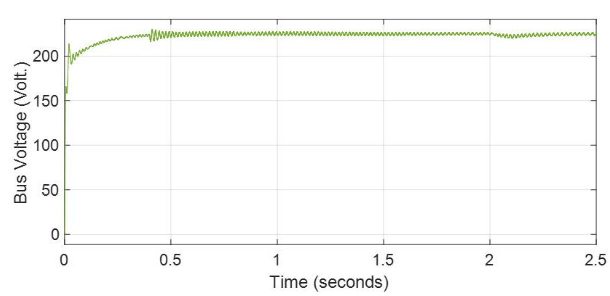

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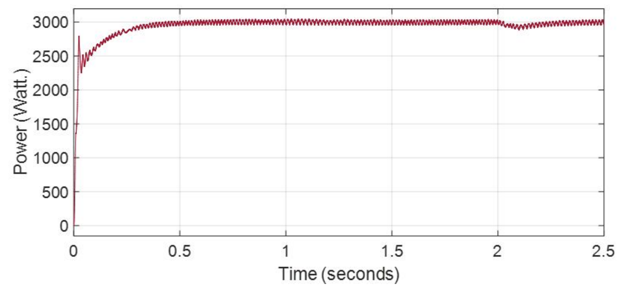

(c)

Fig. 6 Case study:1 (a) Irradiance (b) Bus voltage (c) Power

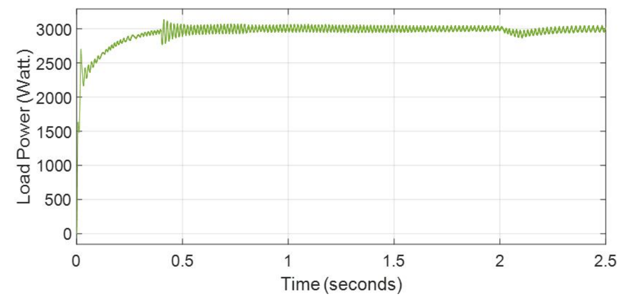

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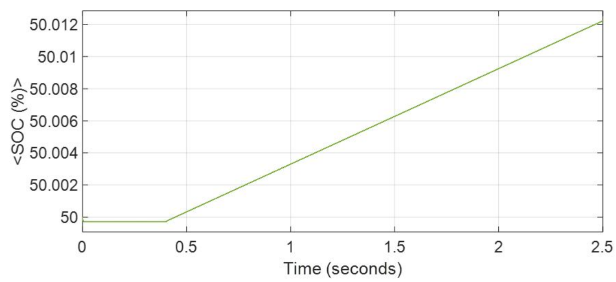
Fig. 7 Case study:2 (a) Irradiance (b) Bus voltage (c) Power



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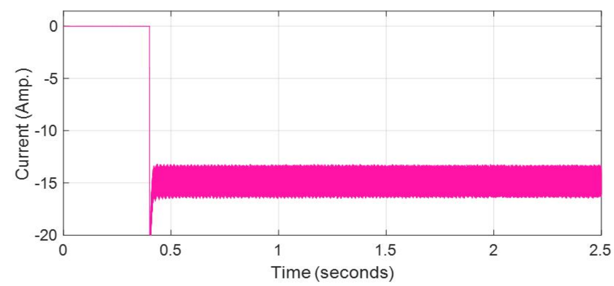

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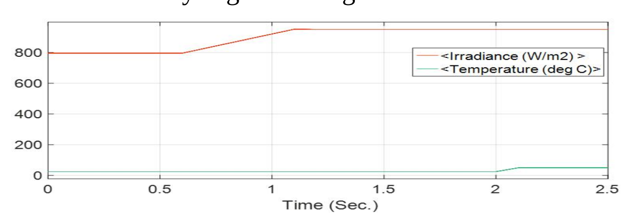
Fig.8 Case study:2 (a) SOC (b) Charging current of battery

The simulation results for the case study: 1 are shown in Fig.6. In this case, the generation by the PV array is greater than the load ($\Delta P>0$) and the SOC of the battery is greater than 90%. Here the operating load is 3KW but the PV array power in the given Irradiation and temperature is 11KW. Since the battery SOC is greater than 90% and the battery is in idle condition, the PV array works in off-MPPT mode to sacrifice the excess power. Thus, provide constant 3KW power to the load and the Stable Voltage Controller generates the pulse for the boost converter which maintains the constant bus voltage (225 V DC) during the variation of the irradiation and temperature.

For the Case study: 2, Fig.7 and Fig.8 represent the simulation results. The generation by the PV array is huge but the load is too light and the SOC of the battery is less than 90%. In this case, the operating load is 3 KW. Thus, to supply the power to this small load, the PV array operates in Off-MPPT mode, that is the Stable Voltage Control block generates the gate pulse for the boost converter. Battery charging started at 0.4 seconds after the bus voltage stabilized. The charge controller charges the battery at a constant current below the safe charging current in such a way as to keep the bus voltage constant. The battery charging current and the SOC of the battery is given in Fig. 8.



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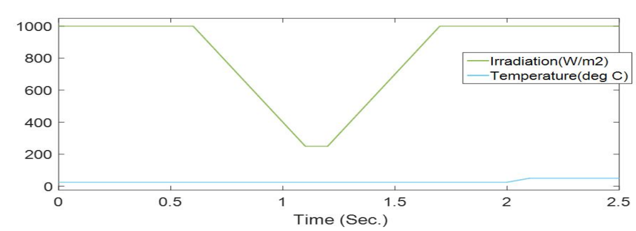

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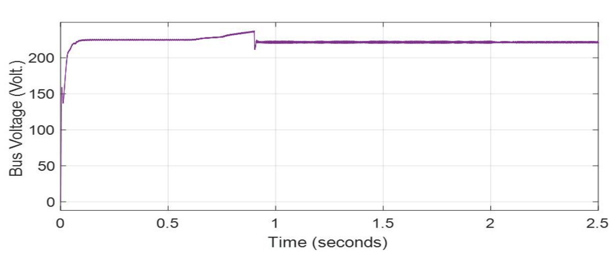

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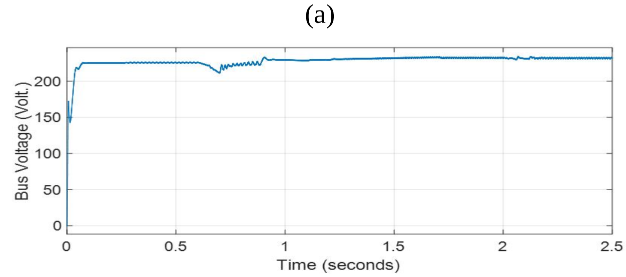

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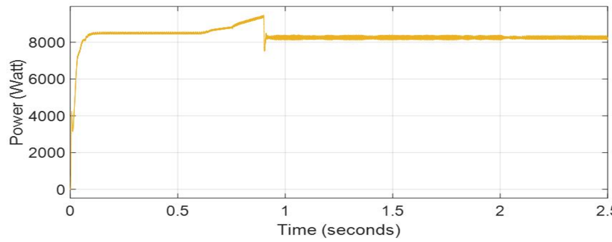

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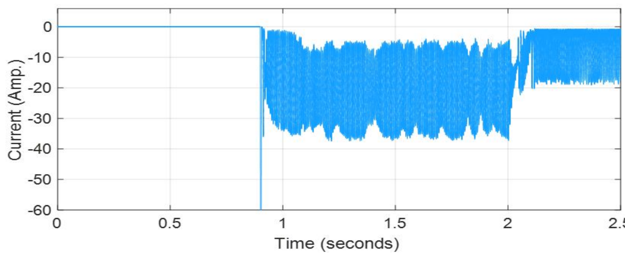
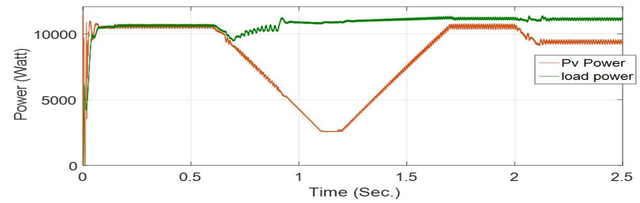


(d)

Fig. 9 Case study: 3 (a) Irradiance (b) Bus voltage (c) Power (d) Charging current of the battery



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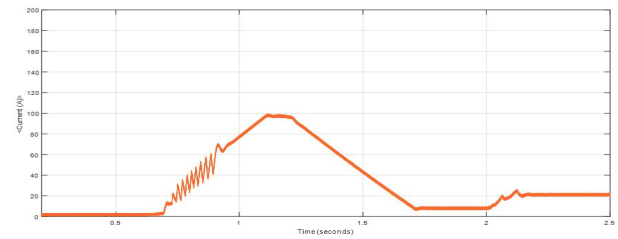
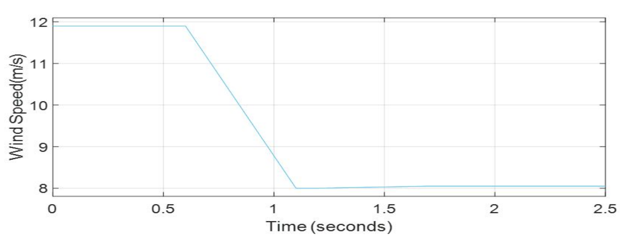


(d)

Fig. 10 Case study: 4 (a) Irradiance (b) Bus voltage (c) Power (d) Discharging current of the battery

Fig.9 shows the simulation results for the case study:3. For this case study, The generation by the PV array is greater than the load and the SOC of the battery is less than 90%. During the simulation, the operating load is 9 KW. And the PV array is operating in ON-MPPT mode at the given irradiation to meet the load. After 0.6 seconds the irradiation increases. So, the power generation and the bus voltage increase. The battery charging starts 0.9 seconds when the bus voltage becomes higher than 235 V. The charge controller charges the battery under the safe charging current at such a rate so that the bus voltage recovers in a short time.

In the case of study: 4, the generation by the PV array is less than the load and the SOC of the battery is greater than 30%. During the simulation, the operating load is 11KW. The PV array operates in On-MPPT mode and gives 11KW power to the load up to 0.6 sec. After .6 sec the irradiation decreases thus the power from the PV the array decreases and the bus voltage tends to decrease. When the bus voltage becomes lower than 215 V then the discharging of the battery starts to maintain the bus voltage constant. Fig. 10 shows that the load power remains 11 KW even after the PV-generated power is reduced due to the decrease of irradiation and increase of the temperature and the battery discharging current increases with the decrease of the irradiation.



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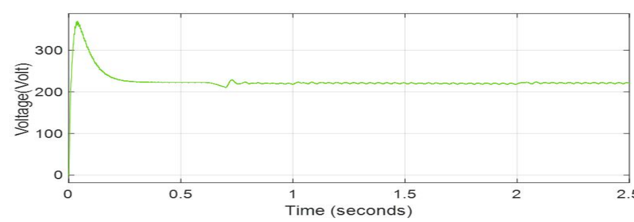

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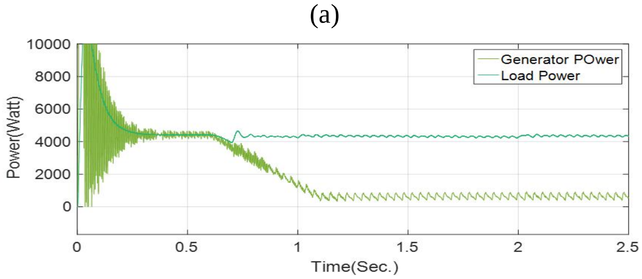

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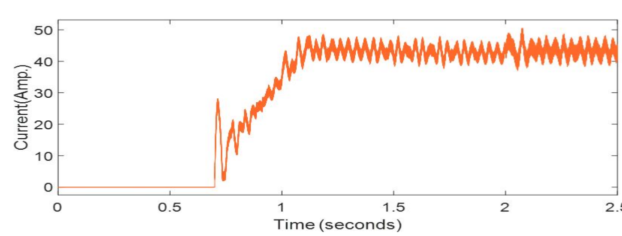

(d)

Fig. 11 Case study: 5 (a) Wind speed (b) Bus voltage (c) Power (d) Discharging current of the battery

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Fig. 11 shows the simulation result for the case study: 5. For this case Generated power from the Wind Energy Conversion System (WECS) is less than the operating load and the SOC of the battery is higher than 30%. During the simulation, the operating load is 4.4 KW. The wind speed starts to decrease after 0.6 seconds. Thus, the generated power and the bus voltage decrease after 0.6 seconds. The charge controller starts to discharge the battery at 0.7 seconds when the bus voltage tends to decrease below 215 V DC. Fig. 11 shows that the generated power is reduced to 1.3KW but the load power is still 4.4 KW. The extra power is supplied by the battery.

V. CONCLUSIONS

The main purpose of this study is to create a model of an isolated DC microgrid using two different non-conventional sources (wind and solar), in MATLAB/Simulink. The proposed model is suitable for remote rural areas or for islands where the grid connection is inconvenient. From the simulation results, the following points are worth noting.

A. In case of the generation increases greater than the load the bus voltage tends to increase then the excess power is transferred to the battery and the bus voltage reduces to the reference value.
B. But if the battery charge level is greater than 90% then the operating state of the boost converter of PV changes from MPPT to the stable DC bus voltage.
C. And in case of the generation decreases than the load then the excess power is transferred from the battery to the load and the DC bus voltage increases to the reference bus voltage

Hence the proposed isolated DC microgrid provides reliable voltage and power management. In future work, an AC grid may be chosen for the proper power transmission and the use of AC loads.

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