Design and Simulation of an Islanded Hybrid Microgrid for Remote Off-Grid Communities

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***Abstract*— To fulfill the Sustainable Development Goal of energy access (SDG 7), renewable energy sources are the main contributing force. This paper focuses on the electrification of remote islanded community with renewable energy sources. This paper proposes two electrification schemes. In first scheme, the whole village is centrally electrified with the use of biodiesel generator, solar PV and with battery banks as storage. With the addition of renewable energy resources in the grid due to its intermittent nature causes fluctuations in frequency. The paper shows the design of frequency controller incorporated with battery to reduce frequency fluctuations. To investigate, a microgrid comprises of diesel generator, solar P.V as generating units with an external battery energy storage system as an ancillary service source to provide primary frequency response is modeled in MATLAB Simulink. In second scheme, a single phase decentralized design is proposed to electrify individual houses with solar and battery arrangement. To assess the effectiveness of the intended system, actual solar irradiance data and load profile of Pahadi village, Morena in Madhya Pradesh, India is taken into consideration.**

***Index Terms*-- Energy access, Hybrid Islanded Microgrid, Primary Frequency Control (PFC), Stand Alone System, Battery to Grid (B2G) and Grid to Battery (G2B)**

I. INTRODUCTION

The fact that energy access is very much important for the overall development of society, demand for electrification increases. There are immeasurable efforts to move the world on the path of sustainability in terms of social, environmental, and economic. Due to growing irreversible effects on the environment from fossil fuels plants in power generation, researchers are working hard to find solutions to make the world pollution-free. One such step is to encourage the technology of Renewable Energy Sources (R.E.S) [1].

To move people from energy poverty tier to non-energy poverty tier in rural areas, electrification is one of the key solutions. To achieve electrification in rural areas two possible schemes can be deployed Grid-connected mode and Off- grid mode. In first, the village can be connected to the main city by adding a new structure to the existing one. This demands for higher investment and time [2]. The second scheme focuses on providing energy access from renewable energy sources in off-grid mode. In off-grid mode, a hybrid connection of solar-biodiesel generation with battery banks as back up can offer continuous power supply without any interruption [3].

With the advancement in solar PV technology along with different inverters and control, scheme 2 is found to be more suitable for electrification to remote islanded communities [4]. In the recent years, solar PV based mini and microgrids have been progressively explored because of their advantages such as abundance of energy, environmental aspect and easy power withdraw as there is no rotating part [5]. To extract more power from PV different Maximum Power Point Tracking algorithms are used and studied. Numerous analyses have been done to investigate the efficient MPPT methods such as Perturbation and observation (P&O), Hill climbing, Incremental Conductance (IC), and artificial intelligence techniques [6].

The increasing use of renewable energy sources in electrification also causes several issues in grid system. Uncertainties of renewable sources like solar PV and wind cause an imbalance between load and generation causing fluctuations in power frequency [7]. This is shown in figure 1 [8]. Therefore, maintaining frequency at 50 Hz or 60 Hz is a challenge [9]. To solve this issue, researchers came up with the idea of providing ancillary services. Solar PV is connected with power electronic devices to the system, thus without any backup support, it does not provide any services to restore frequency to its nominal value [10].

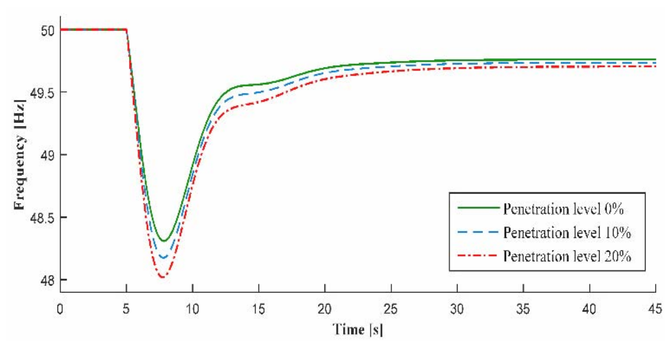

Figure 1. Frequency variation with increasing penetration of renewable energy.

If frequency fluctuates due to the intermittent nature of load and generation in a range of ±0.2Hz to ±0.5 Hz, it is called as normal operating condition. Fluctuations beyond this range can lead to severe damages.

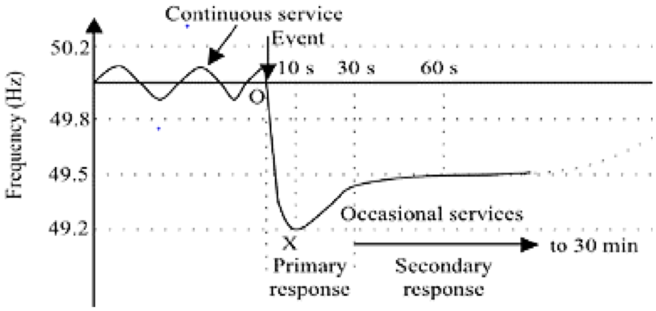

Figure 2. General frequency response stages.

So to ensure reliability in the system, primary frequency response is often included in battery controllers to ensure frequency values [11]. Fig. 2 [11] shows the overall view of frequency response in the system. Thus, to provide primary frequency response, separate battery banks are used in [12] to provide ancillary services [13]. Therefore, in the first section of this paper, a microgrid is modeled with Solar PV, biodiesel generator as primary sources. Later, the battery is added to the system to provide ancillary service support to the system. For this, real-time load and solar PV irradiance data of one of the ill-electrified village has been taken and analyzed [14].

The second section of this article focuses on the standalone installation of solar PV together with the battery management system. Mainly in rural isolated communities' houses have small and single-phase load systems [15]. Here solar PV array is formed by series and parallel modules. The solar PV array is then connected to the battery through a common DC bus with a charge controller. Further, the common DC link point is connected to a single-phase DC/AC converter (inverter) which produces single-phase AC voltage at 220 V [16]. This scheme is thus can provide power to DC as well as AC loads. This scheme can be deployed to provide power in agricultural fields for water pumps or to provide power to community services [17] [18]. In the above-mentioned schemes, second-life batteries can also be used. In this way, discarded second-life batteries can be reutilized. [19]

From the knowledge based on the above-sighted references, this paper focuses on two schemes of electrification for rural isolated communities. In the first scheme, a centralized microgrid is modeled having Solar PV, battery together with a three phase synchronous generator. This system is incorporated with the frequency controller. The second scheme is modeled as a standalone system discussion. Accordingly, paper is formulated and presented. In section 2, the site location for this case study is shown together with its maximum per day load and solar irradiance variation. Section 3 focuses on a centralized three-phase scheme of electrification along with frequency control through the battery management system. Later in section 4, a single-phase stand-alone system is modeled and described. Finally, section 4 comprises of results and discussion part.

II. Site Location: Study Area

A. Location of Case Study

Selected site location is in Morena district situated in Madhya Pradesh state of India. This location (Pahadgarh, Pahadi village) has mainly hilly areas with location 26.3358°N 78.0352°E. This area is surrounded by hills. Due to its rocky land and difficult geography, electric pole erection is quite difficult. The major population of this area resides in a rural area. Therefore, it is easy to electrify this area by hybrid microgrid consisting of both renewable and non-renewable energy sources.

To electrify, the paper proposes two schemes. In first, a centralized 3 phase hybrid microgrid is proposed. This consists of a biodiesel generator, solar PV together with a battery management system. The second scheme focuses on single-phase standalone hybrid systems. This scheme is mainly used to provide power for individual houses, agriculture fields and other single-phase, small scale productive works.

The site location is clearly shown through the three maps. Map (a) is the map of India, in map (b) state of Madhya Pradesh is shown. In map (c) the district of Morena is shown with site location of Pahadgarh, Pahadi village.

B. Load Data of Site

Pahadi village being a rural area has majorly the loads such as residential loads, flour mills, paddy hullers, water pumps etc. In this paper, load of June month is considered as an average load profile. This will ensure the robustness of this study as the maximum variation scenario is being considered. The average load profile of the site is recorded in Table 1.

Figure 3. Map of India. - (a)

C. Solar PV Irradiance Data of Site

Solar irradiance data has been acquired from HOMER for the location of having Latitude and longitude 26.3358°N 78.0352°E respectively. In this research solar, for simulation purpose, data of June month is considered.

Figure 4. Districts of Madhya Pradesh. – (b)

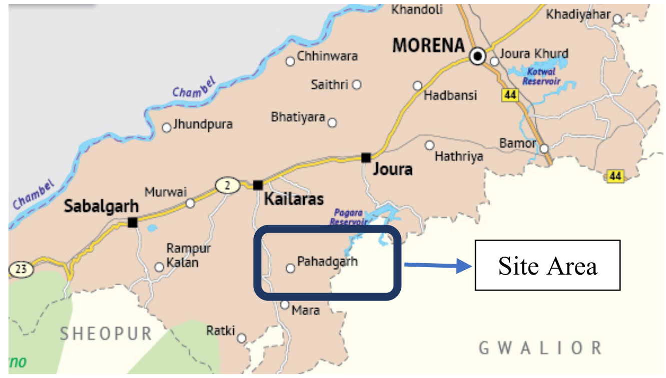

Figure 5. Regions around Morena district. – (c)

TABLE I. AVERAGE LOAD PROFILE (SUMMER)

Time	Load Data (W)
12:00 - 1:00	8100
1:00 – 2:00	8100
2:00 – 3:00	8100
3:00 – 4:00	8200
4:00 – 5:00	8100
5:00 – 6:00	17340
6:00 – 7:00	35501
7:00 – 8:00	43909
8:00 – 9:00	56800
9:00 – 10:00	56800
10:00 – 11:00	56800
11:00 – 12:00	38912
12:00 – 13:00	53611
13:00 – 14:00	53609
14:00 – 15:00	45701
15:00 – 16:00	32307
16:00 – 17:00	26702
17:00 – 18:00	32710
18:00 – 19:00	40601
19:00 – 20:00	44803
20:00 – 21:00	35605
21:00 – 22:00	33407
22:00 – 23:00	15702
23:00 – 24:00	8010

Load profile for the selected site based on Table1 is plotted as shown in Fig. 6. Similarly, Solar PV irradiance data based on Table 2 is plotted as shown in Fig. 7. These profiles are considered for the typical summer (June) season. Here, 24 hours of a day is scaled on the time scale has seven divisions.

TABLE II. AVERAGE SOLAR IRRADIANCE (JUNE)

Time	Solar Irradiance (Wh/m^2)
4:00 – 5:00	85.2
5:00 – 6:00	210
6:00 – 7:00	337.4
7:00 – 8:00	510.1
8:00 – 9:00	649.2
9:00 – 10:00	803.5
10:00 – 11:00	848.9
11:00 – 12:00	790.5
12:00 – 13:00	689.8
13:00 – 14:00	556.9
14:00 – 15:00	397.9
15:00 – 16:00	222.4
16:00 – 17:00	103.5
17:00 – 18:00	81.1
18:00 – 19:00	38.6
19:00 – 20:00	NA

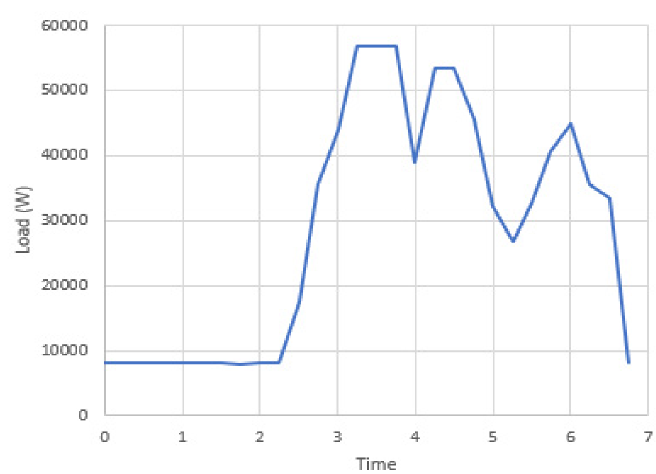

Figure 6. Load Profile of site.

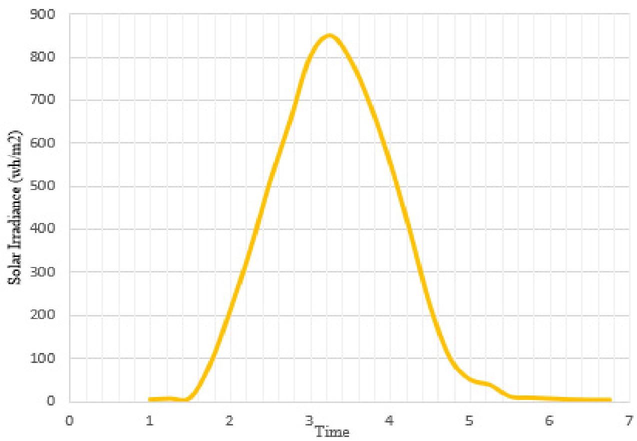

Figure 7. Solar PV Irradiance of site.

III. Three Phase Microgrid Design and Frequency Stability Study (Scheme I)

This section deals with the modeling and design of a centralized three-phase microgrid system. In this structure, the microgrid consists of biodiesel Genset, solar PV supported by the battery management system. The three-phase system voltage is 230 V line to phase. Detailed modeling of each constitutes of a microgrid is as shown in the following subsections.

A. Synchronous Generator

The detailed modeling of the three-phase synchronous generator is shown in Fig. 8. Fig. 9 shows the detailed modeling of the governor which is responsible for frequency stability.

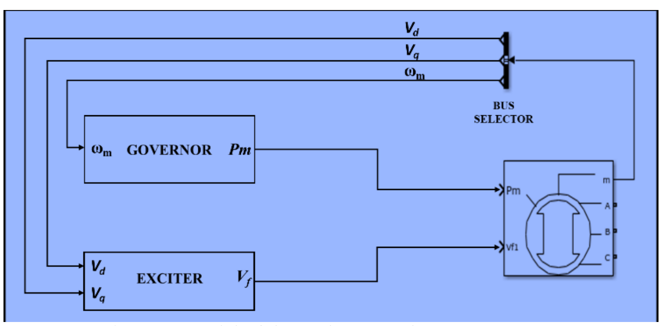

Figure 8. Model of three-phase synchronous generator.

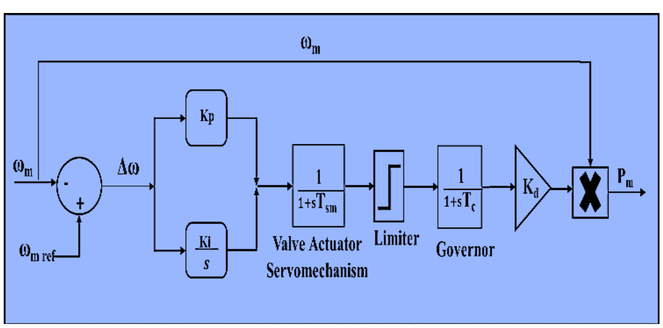

Figure 9. Detailed modelling of Governor.

B. Solar PV and Battery Management (Primary Frequency Controller)

Further, solar PV is modelled for the system. The parameters and sizing are chosen based on peak solar hours which derived from average solar irradiance data as shown in Table 2. The solar PV system is connected with the DC/DC converter together with the Maximum Power Point Tracking algorithm. Further, it is connected to inverters to convert DC into AC. As renewable generation is integrated into the system due to its intermittent nature cause variations in frequency. To reduce these frequency variations, in this research battery management system is introduced. A primary frequency controller is introduced in the battery. This frequency controller first detect change in frequency signal Δf. This signal is then multiplied with a suitable droop control coefficient. This signal then decides the output power of the battery [7]. Deadlands are added to the system to prevent the activation of the controller for small fluctuations. Its value is 0.001 Hz. Limiters are then added to the system to limit the power output of the battery according to the SOC. The controller is as shown in Fig. 10. This controller is based on grid to vehicle (G2V) and vehicle to grid (V2G) strategy. Here since author uses an actual data of E TUK-TUK battery. Here, battery is of 100 Ah, 100 V.

C. Microgrid Parameters

The proposed scheme of whole microgrid is as shown in Fig. 11. The microgrid is modelled in MATLAB Simulink. Ratings and specifications of various components are shown in table 3.

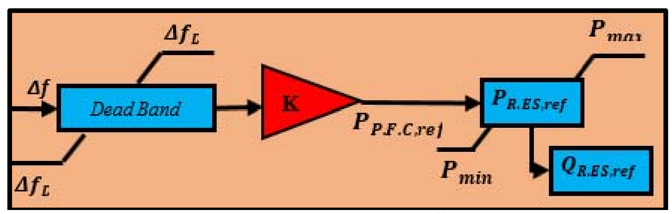

Figure 10 Frequency Controller.

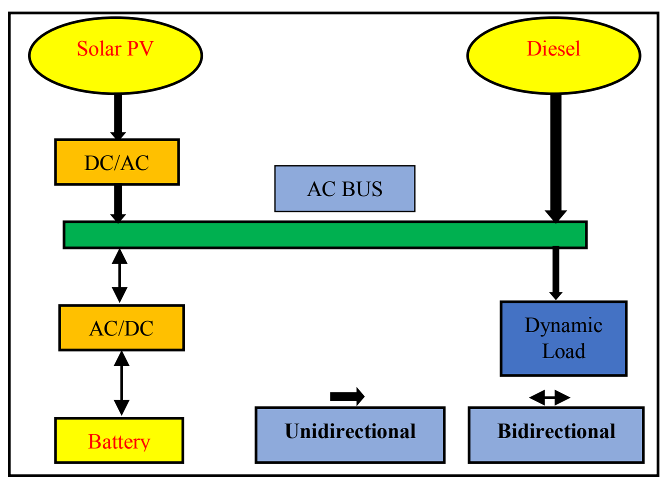

Figure 11 Overview of Microgrid.

To investigate the frequency response a microgrid as stated in Fig. 8 is designed. Microgrid consists of Solar PV Panels, a conventional synchronous generator with battery. All the designing parameters are listed in Table 3.

TABLE III. MICROGRID DESIGN PARAMETERS

Source	Values	Max. Capacity
Governor droop	1 Hz/pu	40 kVA
Maximum Power (M.P) of 1 module (W)	213	50 kW
Voltage at M.P.P (V) for 1 module	29	
Solar P.V Modules in series	21	
Solar P.V strings in parallel	12	
Solar P.V series D.C voltage (V)	700	
E.V Battery nominal capacity (Ah)	100	25 kW

D. Results and Discussion for Scheme 1

Scheme 1 is modeled to electrify the whole community, providing three-phase power. With the irradiance data shown in Table 2, solar PV power output is shown in Fig. 9. Since, solar irradiance high during mid-day therefore, solar PV power output is high during this time.

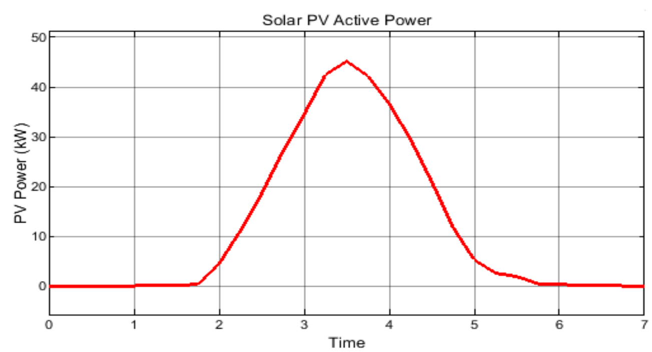

Figure 10. Solar PV Active Power Output.

With the variation in solar PV output and load, frequency fluctuates around its mean value (50 Hz). To control these frequency fluctuations, primary frequency response controller is introduced in battery.

From Fig. 6, peak load appears between 3rd and 4th unit of time. System Frequency drops as generation is lower than load demanded. Similarly, it goes up when the load is less than the generation. To examine the frequency reaction, two cases are simulated. In the first case, the system is delivering power with a diesel generator and solar PV. In this case, the primary frequency controller from the battery is deactivated. In the second case, the battery frequency controller is activated. With the variation in solar and load profile, frequency is response is as shown in Fig. 11. The minimum and maximum points in frequency response are recorded in Table 4.

As load suddenly decreases after 6th-time unit during nighttime therefore frequency increases and reaches its zenith point. Frequency shoots up to 51.39 Hz when no control is provided. To reduce this, shoot up of the frequency, an external battery is added to the system with frequency control. The extra power of the generator is absorbed by the battery and thus bal-

TABLE IV. MICROGRID DESIGN PARAMETERS

Type of Control	Zenith Points		Nadir Points	
	Value	Time	Value	Time
No Control	51.39	6.6	48.8	4.3
PFR _Battery	50.52	6.6	49.41	4.3

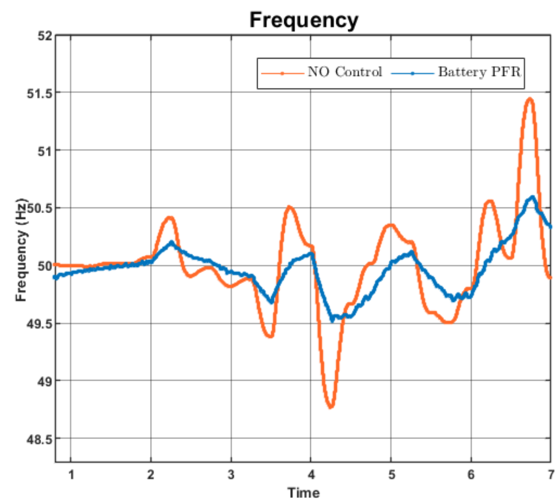

Figure 11. Frequency response of system.

ancing the load generation profile. Similarly, at 4.3rd unit of time-frequency has its nadir point. Without battery frequency control, frequency drops to 48.8 Hz. At this point, the battery can provide the demanded extra power to the system and stabilize frequency. This bidirectional power flow by battery is shown in Fig. 12. This concept can be called as Battery to Grid (B2G)and Grid to Battery (G2B).

During the nadir points of frequency as shown in Fig. 11, the battery can discharge and injects power to the grid. Similarly, at 6.725 seconds, the battery absorbs the extra power from the grid and therefore, improving frequency response.

Accordingly, the SOC of the battery is shown in Fig. 13.

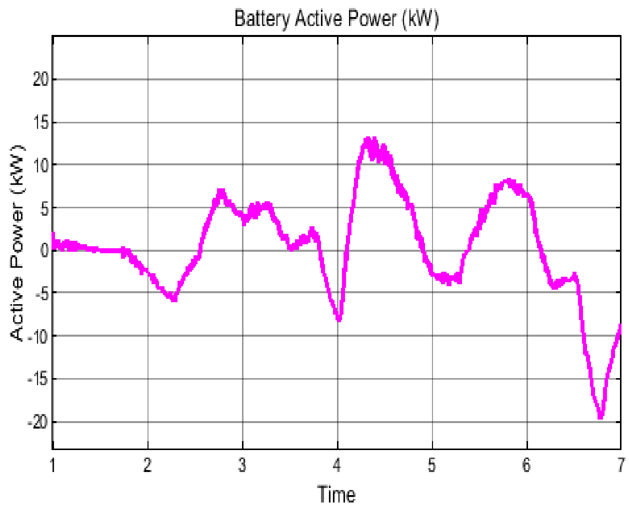

Figure 12. Bidirectional Battery Power Flow.

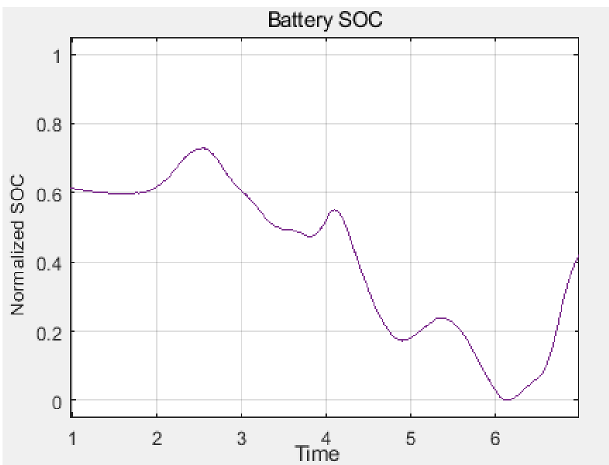

Figure 13. Battery State of Charge during absorption and injection of power.

IV. Stand-Alone Single Phase Microgrid Design and Simulation (Scheme II)

This scheme is designed to provide power in standalone mode. This system can be mounted to residential houses, cold storages, agricultural pumping stations, etc. Here in this research, a 230 V single-phase system is designed. System consists of a DC bus at which solar PV and battery management system is connected to supply DC loads (LED lights). The common coupling point at DC bus is then further connected to AC/DC single phase inverter to provide power to AC loads.

A. Power Flow Scheme (Working)

In this scheme, a charge controller for the DC bus is modeled. This controller will maintain a constant voltage at the DC bus. Controller working is shown in the flow chart, Fig. 14. When the solar PV irradiance is greater than 500 Wh/m^2, solar power provides power i.e. it charges the battery as well as supply power to DC loads and AC loads through inverter. When the solar irradiance is below 500Wh/m^2, battery will solely discharge to provide power to different loads.

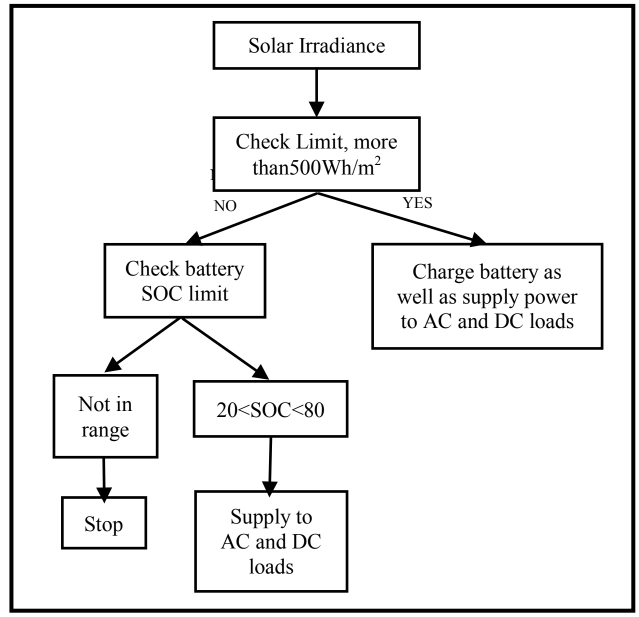

Figure 14 Flow chart for power management in the standalone system.

B. System Parameters

The overall standalone system is designed as per scheme shown in figure 15.

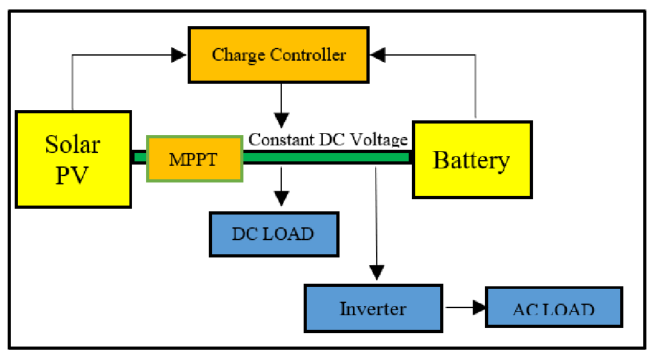

Figure 15. Design of standalone single-phase system.

Specifications and values of different components are mentioned in table 5.

TABLE V. System Design Parameters-Scheme II

Source	Values	Max. Capacity
Common DC bus voltage	100 V	
Maximum Power (M.P) of 1 module (W)	213	3.5 kW
Voltage at M.P.P (V) for 1 module	29	
Solar P.V Modules in series	3	
Solar P.V strings in parallel	6	
Solar P.V series D.C voltage (V)	87	

Source	Values	Max. Capacity
E.V Battery nominal capacity (V,Ah)	72V, 100Ah	
AC Load	2 kW	

C. *Results and Discussions*

For solar PV, irradiance is chosen as shown in table2 and its solar PV (rooftop) power output is shown in Fig. 16. With battery 72V, 100Ah, solar PV is connected to battery. This constitutes the DC system. The following controllers are set up in the system to make it stable.

- MPPT (Maximum Power Point Tracking) algorithm
- DC/DC Boost Controller for Solar - This is used to boost DC solar voltage. Controller gets its duty signal from MPPT controller. This ensures the constant output voltage at DC bus i.e. 100V.
- Charge Controller for Battery – Here, the error signal is first generated by considering reference bus voltage (100V) and DC bus voltage. This error signal is then generated a reference current signal for battery. This reference current finally controls the battery current through the PID controller and produces a duty ratio. This duty ratio further regulates the bidirectional switches to check the power flow from battery i.e. charging and discharging.
- This constitutes the whole DC system, and it is connected to a DC Load (1kW).

Further, the DC system with constant DC bus voltage is connected to a single-phase DC/AC inverter to provide power to AC loads [20]. The inverter constitutes the input capacitors, high-frequency transformers (25kHz), and an H-bridge converter. This converter is triggered through a synchronizing 230 V signal controlled by a PI controller. AC load used

The results of the DC system are as shown in Fig. 16, Fig. 17, Fig. 18, and Fig. 19. Fig. 17 shows the variation of reference DC voltage and actual DC voltage. As there is variation from reference voltage is less (less than 5V), this will ensure the robustness of the system. Fig. 18 shows the battery current with reference current value. The battery current is following the reference value, this ensures the robustness of the controller.

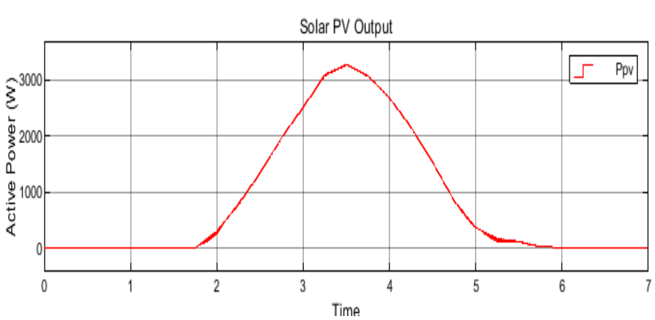

Figure 16. Solar PV output.

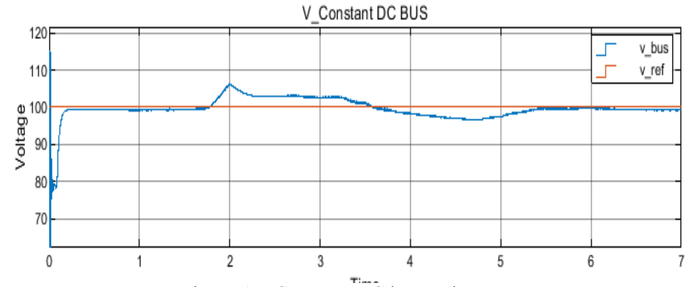

Figure 17. Constant DC bus Voltage.

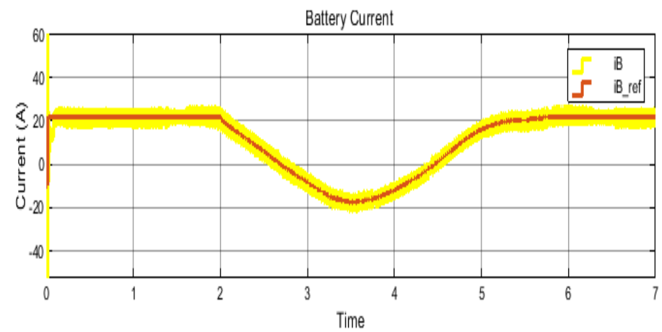

Figure 18. Battery Current.

Fig. 19 shows the charging and discharging profile of battery. As solar PV irradiance in the initial and final hours of the day is lower than 500Wh/m^2, the battery is discharging as shown in Fig. 19. When irradiance is greater than 500Wh/m^2, solar PV provides power to AC and DC loads as well as charges the battery. The output of the inverter is shown in Fig. 20. The single-phase AC output voltage has a peak value of 324.8V which is equal to 229.66 V RMS value. The total harmonic distortions are less than 1%. This validates the robustness and stability of the controller and system.

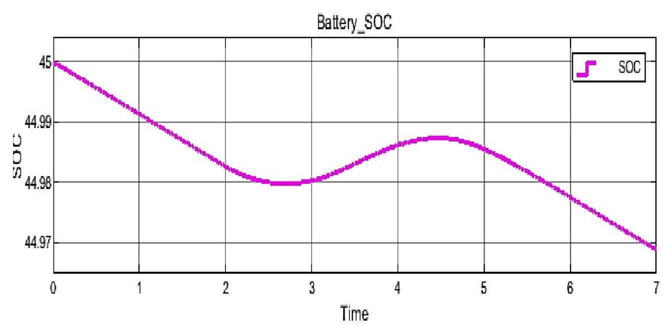

Figure 19. Battery State of Charge.

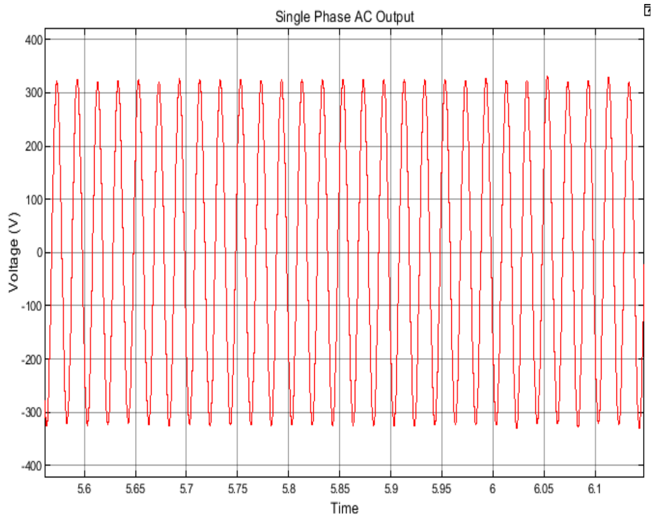

Figure 20. Single phase AC voltage output.

V. CONCLUSION

The design and simulation study of two schemes is done in this research to electrify an ill-electrified village in India. The first scheme consists of a biodiesel generator together with varying solar PV and provides three-phase power. Integrating R.E.S for electricity generation, the community can move from the energy poverty tier to the non-energy poverty tier. The community and hospital services are very much needed in a rural community and thus scheme 1 can be used to provide power to fulfil these demands. Besides community services, another important load in rural community are residential loads. To provide power in houses, paper proposes standalone hybrid solar battery design as scheme 2. This scheme uses solar PV together with battery controller. This scheme can provide power to both AC and DC loads. As shown in results, expected values and responses are coinciding with reference values and THD values are less than 1%. This ensures the robustness of the controller and system. This scheme is mainly designed to reduce the use of diesel generator. Thus, reducing greenhouse gas emissions and supporting sustainable development goals. Scheme 2 can further be incorporated into electric vehicles or with small E TUK TUKs. Thus, can be used as a mobile battery storage facility. Moreover, in the future second-life batteries can also be incorporated with the above-mentioned schemes to eradicate energy poverty. This will ensure the more optimized usage of waste and discarded batteries.

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