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Heuristic Controller for Wind-Diesel System with Energy Storage For Standalone Application

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Abstract—Wind-diesel systems are a popular choice to provide power in remote areas in standalone mode. Their conventional design considers AC bus as the common bus between the wind, diesel and energy storage component. The AC power at the AC bus is directly fed to the load. However, it creates problems, such as frequency regulation, voltage regulation, and low efficiency due to theuse of dump load. This paper proposes a topology with a common DC bus, where the wind-diesel and battery are connected. The topology uses small rotor wind turbines (SRWT) in the wind-diesel system. The advantages of using SRWT are (i) low cost, (ii) small in size, (iii) low-speed operation, and (iv) affordable for rural communities. This topology eliminates the problems encountered with common AC bus system. Moreover, to maintain the continuous power flow and voltage level a heuristic controller is developed. Thus, it provides a better performing system. The system is simulated in MATLAB, and the results show that the proposed topology provides improved operation to the system.

Keywords—Wind-Diesel System, Small Rotor Wind Turbine, Energy Storage

I. INTRODUCTION

Off-grid power supply systems are an attractive and sustainable mode to supply energy. It is used to provide power to communities located in remote or islanded area, having difficulty in achieving grid connection, due to political, economic or location constraints [1]. Wind-diesel system with battery hybrid system is considered to be one of the best alternative solutions to meet the electricity demand of numerous remote consumers. The rationales behind this are installationand operational cost, even at mediumwindpotential areas [8]. It is a hybrid system, where wind and diesel generators operate in a complementary manner. The wind generator acts as a primary source of energy and diesel generator serves as a secondary source. The diesel generator complements the operation of the wind generator. The operating modes of this system are tabulated in Table-1 [5].The wind operates when sufficient amount of wind is available, and the diesel engine operates when the wind is not available.In case, the wind is available, but surplus power is not available, the deficit of the power is provided by the diesel generator.To enhance the reliability, the energy storage is also added to the system.The energy storage system used with it to maintain voltage and power levels chargein the windonly mode. It provides power in all other modes. The general architecture of the wind-diesel system is shown in Fig. 1. It makes the power available under all circumstances. Wind-diesel systems have been used in combination with abattery and other sources, such as photovoltaic, etc.

Conventionally, the wind-diesel systems are connected to the load through a common AC bus. As the output of the diesel generator is AC, it is directly connected to the AC bus. The output of the wind generator is AC with variable frequency. To connect it to the AC bus, it is converted to AC at a fixed frequency with AC/DC and DC/AC converters. Similarly, the battery is connected to the AC bus through the DC/AC power electronic converter. The complete conventional structure is shown in Fig. 2(a). Though this structure meets the target of providing energy to the consumers; it suffers from several drawbacks,

- The system requires additional controllers to regulate the load frequency.
- To maintain the voltage level controllers are required.
- In case, the sources need to be operated at the same time. They need to be synchronized.

To regulate the frequency in AC system, the active power needs to be balanced. A dump load is

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connected at the load side. Also, some amount of power lost in the conversion process, resulting in decreased efficiency of the system. Thus, the architecture used for the analysis needs to be modified. In some microgrid systems, this connection is modifiedas making a DC bus as the common bus and converting power into the desired form (AC/DC). However, the system has not been used for a wind-diesel system.

TABLE I. MODES OF OPERATION OF WIND-DIESEL SYSTEM

Mode	Diesel Generator	Wind Generator	Energy Storage
Wind Only	Off	On	On
Diesel Only	On	Off	Off
Wind-Diesel	On	On	Off

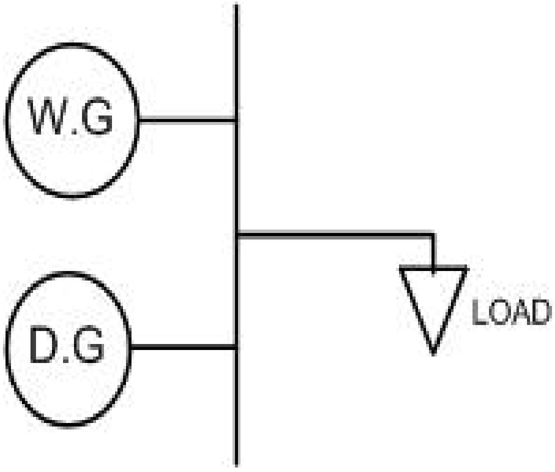
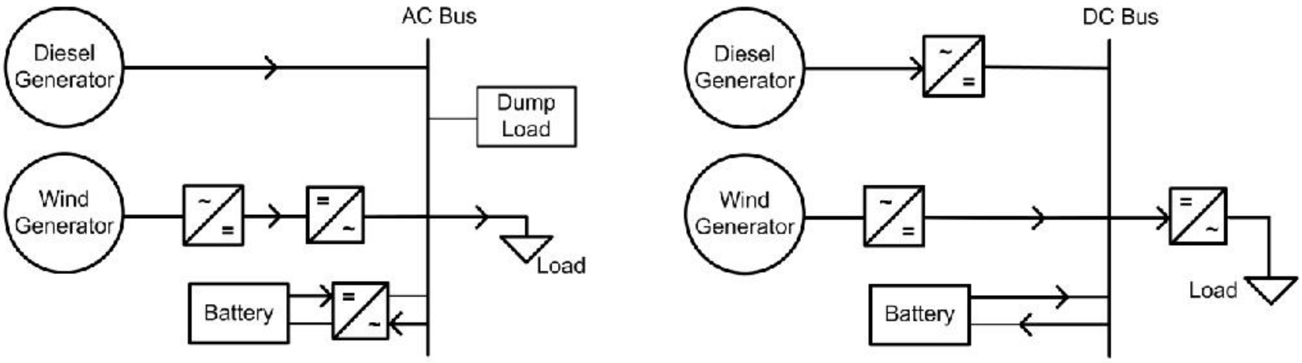


Fig. 1. Schematic of wind-diesel system



(a) (b)

Fig. 2. Wind-diesel system connection (a) conventional, and (b) modified

This paper attempts to present a modified structure for the wind-diesel system as shown in Fig. 2(b). In this structure, the common AC bus is replaced by a DC bus. The batteries being a DC component are directly connected to the bus, whereas the diesel generator and the wind generator are to the bus through a rectifier. The output of the DC bus is converted to AC through an inverter. The highlight of the present work is the use of inverter for this purpose. This configuration allows overcoming the drawbacks of the conventional model, as

- Inverter regulates the frequency. So, the requirement of a separate frequency controller is eliminated.
- The inverter also regulates the voltage levels.
- As the dump load is eliminated, a large size battery can be used to store excess energy. Thus, theefficiency of the system improves.

The topology uses small rotor wind turbines (SRWT) in the wind-diesel system. SRWT allow operations at low speeds of few metres per second at a low cost, making it useful and affordable for rural communities.

The rest of the paper is organized as follows: Section-II discusses the models of the wind generator, diesel generators, and batteries. Section-III presents the modeling of power electronic converters. Results are discussed in Section-IV, and finally, conclusions are drawn in Section V.

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II. Modeling of Components

In this section, the models of the wind and diesel generators of the wind-diesel system are discussed. In deciding the configuration of the component, the cost has been taken as the prime factor. The low cost of the equipment has been ensured by the abundant availability of the model.

A. *Wind Generation System*

In this work, the wind generator system used is an SRWT. The SRWT considered in this work is a variable speed wind turbine based on permanent magnet synchronous generator (PMSG). The generator is directly coupled to the rotor shaft. The generator is aconnected to the diesel and battery through the rectifier system as shown in Fig. 3 [18].

The power generated by the wind turbines is presented by the relationship given by (1).

$$P_w \, X \frac{1}{2} c_p \circ A V_w^3 \qquad (1)$$

where,P_W is the power extracted from the wind,ρ is the air density, C_p is the power coefficient, V_w is thewind speed upstream of the rotor [m/s], and A is the area swept by the rotor [m^2].

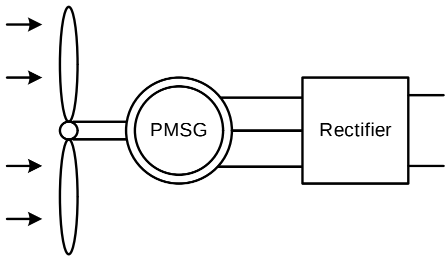

Fig. 3. Variable speed wind turbine system equipped with PMSG

B. *Diesel Generation System*

Diesel generator system is acombination of diesel engine and the synchronous generator. The diesel engine works as a prime mover, whereas the synchronous generator works as apower source. The diesel generator in the simulation is modeled to control the voltage level. The voltage reference (in pu) is provided to the controller and the speed of the generator is fed back to the controller. Based on the variation of the terminal voltages of the generator, the speed of the generator is controlled by the generator. The schematic of the voltage controller and the diesel generator is shown in Fig. 4 and Fig. 5 [19]. The AC output of the diesel generator is converted to DC through the rectifier.

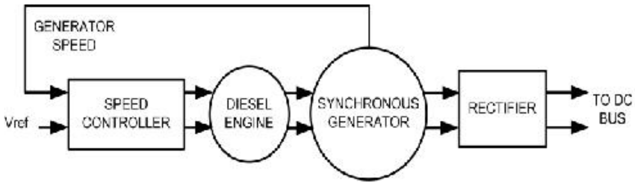

Fig. 4. Schematic of diesel generator

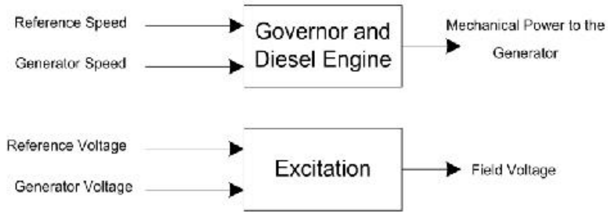

Fig. 5. Controller of the diesel generator

C. *Battery System*

Energy storage is a vital component of thehybrid energy system. They ensure that the continuity of power is maintained in case, sufficient power is not available from the energy sources. A number of battery systems are available in the market, such as alead acid battery, Ni-MH battery, and Li-ion battery, etc. Amongst these different batteries, lead-acid batteries are very common and low cost. Thus, they have been considered in the simulation. The battery is considered as a voltage source in series witha resistance, as shown in Fig. 6. The internal resistance R_0 is assumed to remain constant, and the internal voltage E varies with the state of charge (SOC). The voltage, current and the SOC of the battery are monitored continuously. In case the battery goes below a threshold SOC, it stops supplying power. Since, the output of the battery is DC, it directly connected to the common DC bus.

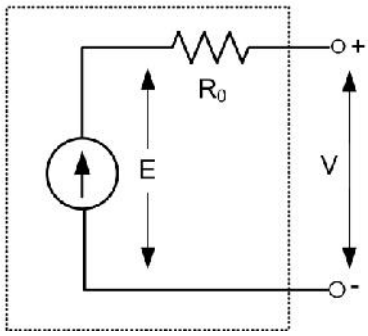

Fig. 6. Schematic of diesel generator

Mathematically, the terminal voltage is given as,

$$V \, X E \, Z I R_0 \qquad (2)$$

To operate these three components in a synchronized manner, it is essential that the components should be optimally sized. The component sizing is essential.

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Also, these components need to work in a coordinated manner to ensure acontinuous supply of power to the load. These aspects of the system design are discussed in the next section.

III. System Operation

Here, the system considered consists of three different source, wind generator, diesel generator and battery energy storage. The complete structure of the system is shown in Fig. 7. The cost being the primary concern for the design, the optimal sizing of the three components becomes important. Also, the operation of these three sources needs to be coordinated properly to ensure effective utilization of energy.

A. Optimal Sizing

To optimally size the components the following cost based objective function considered in [20]. The cost consists of the installation, operating and maintenance cost of the wind generators, diesel generator, and battery. The objective function aimed at minimizing the total cost of the system. The problem being quadratic in nature is solved using the quadratic programming technique. The optimization process is constrained by the (i) Balance between the energy supplied and energy consumed, (ii) Maximum power generation available for the diesel generator, wind generator, and battery capacity, and (iii) SOC constraint on the battery operation. The algorithm used first considers the wind data of the area to obtain the power available through the wind and initial capacity of the diesel generator and battery are selected. Then, based on the load profile the cost is minimized considering the cost. Based on the peak value of the load, the maximum generation capacity of each component is selected. The results obtained are discussed in Section IV.

B. Controller Design

To obtain the coordinated operation between the three sources in the hybrid system a heuristic controller is developed. The controller ensures that the modes of operation described in Table are successfully implemented. Also, it takes care of the ambiguity arising due to which source needs to supply the load. The algorithm for the heuristic controllers developed is shown in Fig. 7. The controller continuously monitors the wind speed, SOC of the battery to decide the operating mode of the system. Since, diesel generator can be operated by the operator as per the requirement. Thus, the operation remains to coordinate the wind generator and battery with the diesel generator. As shown in Fig. 8, the wind speed and SOC values of the battery compared to the threshold value, which is 6 m/s for the wind speed and 70% for the SOC of the batteries. In case the SOC falls below 30%, the battery stops supplying the load.

C. System Operation

The system configuration shown in Fig. 8 operates in different modes using the controller discussed above. The controller senses the wind speed falling on the blades of the wind turbines and the SOC of the battery. If the wind speed and the SOC of the battery is higher than the threshold set in the controller and the switches S_B and S_W are closed. The operating condition achieved, is termed as wind only mode. In diesel only mode, the wind speed falls, whereas the battery maintains it'sSOC, the switch S_W is opened, and the S_B and S_D are closed. In wind diesel mode, the switch S_W and S_D are closed, whereas the battery switch S_B is opened. Moreover, the battery is now connected to the wind and acts as a load during charging. The results obtained through these different modes of operation of the wind diesel systems are discussed below.

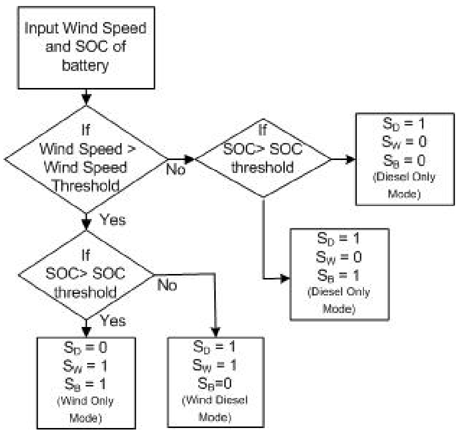

Fig. 7. Algorithm of the controller

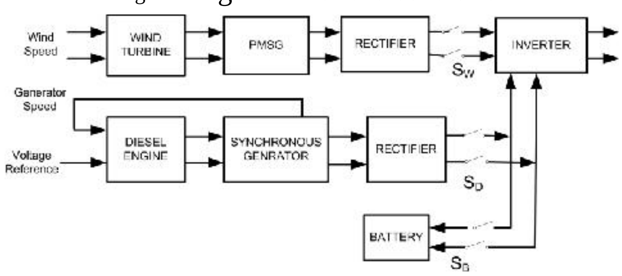

Fig. 8. Schematic of system configuration

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IV. Results and Discussions

The wind-diesel systems are ahybrid system, where the operation needs to be coordinated. For the wind-diesel system considered in this work the optimally sized wind, diesel and battery system is considered. The optimal sizing is performed considering the load profile []. The optimal sizes for the wind generator, diesel generator, and battery system are 85 kW, 70 kW, and 30 kW, respectively. For the wind generation, a permanent magnet synchronous generator (PMSG) of the same capacity is considered with rated with thespeed of 6 m/s. This speed is considered as threshold speed. For the battery system, the lead-acid batteries are considered. The complete system is simulated in SIMULINK platform, with a rated voltage of 440 V. The operation of the hybrid system is coordinated using the algorithm discussed in Fig. 7. The operation of the controller revolves around the availability of the wind generation to meet the load demand. The coordination primarily deals with the wind generator and battery. The diesel generator is operated whenever; sufficient resources are not available to meet the demand.

Based on this, the wind profile as shown in Fig. 8 is considered for the wind diesel system. As per the control algorithm, the battery and diesel generator are connected to the bus system, when the speed is less than 6 m/s, depending on the SOC of the battery. At 6 m/s the diesel is operated with the wind generator. Since, sufficient power is available with the wind generator, the power requirement from the diesel generator is low. In all other conditions, the operation is governed by the control algorithms.

For the wind speed profile considered, the wind-diesel system with thebattery as shown in Fig. 8 is simulated, and the switching of the different sources is considered. The switching profile of different sources is recorded and shown in Fig. 10. For 0 to 2 sec., the wind speed is 5 m/s, so the S_D and S_B are switched on, so diesel generator and battery are connected to the load. For 2 to 4 sec., the S_B is off, and S_W is switched on. The S_D remains on during this period. For 4 to 6 sec., the wind speed becomes higher than the rated, 7 m/s. So, the S_W is on along with S_B, whereas, the S_D is turned off. For the 6 to 8 sec., the speed of wind turbine again becomes low. Therefore, the S_W is turned off, and S_D is turned on. The state of S_B depends on the SOC of the battery at that instant of time. If it is higher than 60%, it is on; else it becomes off.

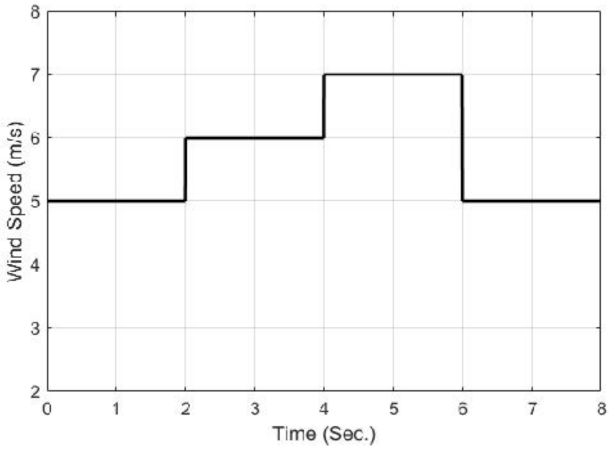


Fig. 9. Wind speed profile for wind generators

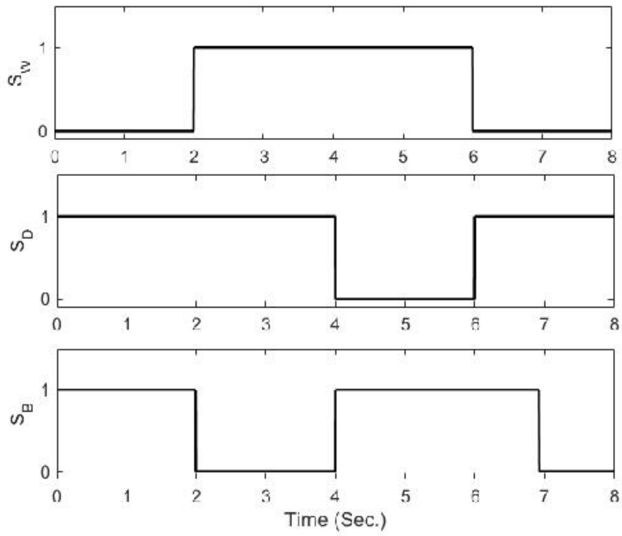
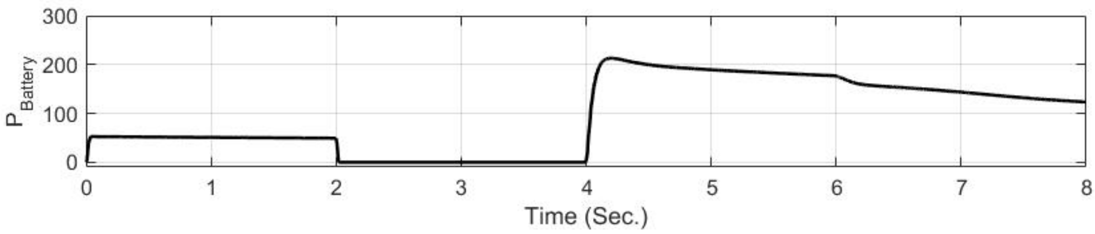


Fig. 10. Switching profile of different sources in the wind-diesel system with battery



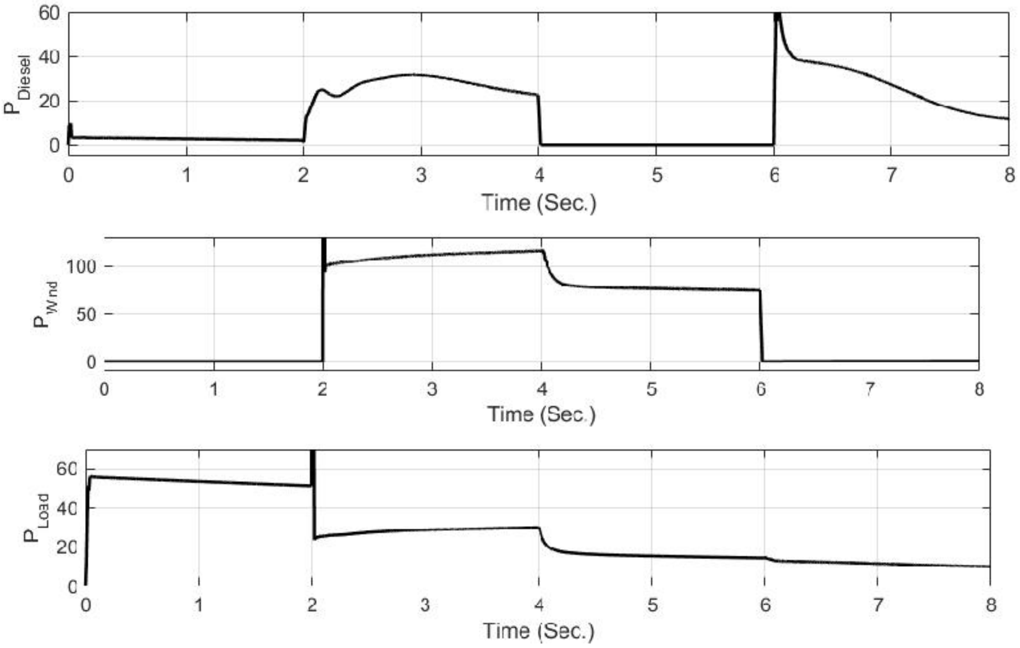


Fig. 11. Variation of power from the source and the load for the wind-diesel system

For the switching profile of different sources, the variation of power is also recorded as shown in Fig. 11. It shows that the different sources, switch effectively to supply power to the load. This switching of different sources also allows observing the different modes of operation of the wind-diesel system as shown in Table I. The operation of the controller is also dependent on the SOC of the battery. The SOC of the battery is also recorded as shown in Fig. 12. It shows that the battery charges during 2 to 4 sec when surplus power is available in the network due to switching on of wind and diesel generator.

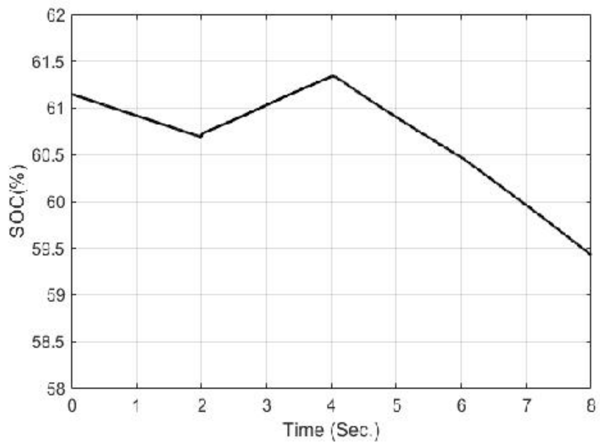


Fig. 12. Variation of SOC of battery with switching of different sources

V. CONCLUSIONS

Wind-diesel systems are a popular choice to provide power in remote areas in standalone mode. Their conventional design considers common AC bus to connect wind, diesel and energy storage components.The AC power at the AC bus is directly fed to the load. However, it creates problems, such as frequency regulation, voltage regulation, and low efficiency due to theuse of dump load.The structure proposed in this paper allows a common DC bus, where the wind-diesel and battery are connected.This topology eliminates the problems encountered with common AC bus system. Moreover, to maintain the continuous power flow and voltage level a heuristic controller is developed. The controller is simple and allows switching of different sources as per the requirement of the load and condition of the source. The results show that the proposed approach successfully meets the requirement of the power demand by switching the sources. The controller is simple allows cost effective implementation for rural applications.

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