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Optimization of a PV with Diesel-Battery System for Remote Villages

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ABSTRACT

This paper discusses the long-term performance and monitoring issues related to integrating a battery bank and a photovoltaic (PV) array into electric power systems for remote villages like those found in Asia and many other parts of the world. The long-term performance tool developed in MATLAB™ Simulink can be used for design, simulation, and optimization of these types of hybrid power systems. An integral part of the optimization process is remote monitoring and ultimately control of the system. This project involves the installation of various types of sensors on power systems in remote villages and then the analysis of their performance. The sensors transmit data to a central computer commonly known as Remote Terminal Unit (RTU) that is in close proximity to the system. The current model consists of a diesel-electric generator, a battery storage bank, and a PV module connected to a common grid to form the hybrid system. System performance is evaluated based on fuel savings relative to the diesel-only case. An example is presented based on an actual test system in the remote Alaskan community of Lime Village. The simulation results show significant savings in the fuel consumption due to the introduction of the battery bank and the photovoltaic array into the diesel-only system.

1. INTRODUCTION

THE need for energy-efficient electric power sources in remote locations is a driving force for research in hybrid energy systems. This topic is very important for many developing countries in Asia and other parts of the world. According to the World Bank, a group which provides a source of development assistance for developing nations, Asian countries are expected to spend \$600 billion in the coming decade to satisfy energy demands [1]. Many countries in Asia will continue to harvest their energy needs from imported oil and fossil fuels. Renewable energy is becoming a promising alternative to fossil fuels in remote locations. The main renewable energy sources available in these countries include: solar, wind, biomass, geothermal, and hydro-electric power [1].

Stand-alone hybrid power systems are often more cost-effective than utility grid extensions mainly due to the high cost of transmission lines. About 60% of the households and 70% of the villages in Asia have no access to the electric utility grid. Some of these communities rely on diesel generators for electric power [1,2]. This is also true for remote communities like those found in Alaska. Based on energy consumption studies compiled by the US Department of Energy, Alaska spends \$28.71 per million BTU for energy versus \$19.37 per million BTU for the rest of the United States [3]. It is very expensive to transport fuel for diesel electric generators (DEGs) in some villages of Thailand [2] and Alaska [4] due to remoteness of the site. Furthermore, there are issues associated with oil spills and storage of this fuel [5]. Therefore, PV, wind and other renewable sources of energy are being integrated with DEGs to help reduce the fuel consumed by the DEGs.

There is growing interest in renewable energy conversion systems among the power utility companies. The use of renewable energy sources in remote locations could help reduce the operating

cost through the reduction in fuel consumption, increased system efficiency and reduced emissions [6,7]. In the past decade, more than 700 kW of the PV modules have been installed in Thailand. A PV working group has been set up to help promote the realization of PV in Thailand [8]. In [2] Kruangpradit et al describe the design, implementation and evaluation of pilot hybrid renewable energy systems for electrification of remote villages in Thailand. A small battery bank is often used in conjunction with the PV array to allow for ‘the maximum energy transfer to the grid’ [9].

This paper presents a model based on an existing hybrid electric power system for a remote location in Alaska. The input data to the model is acquired using a remote terminal unit (RTU) which must first be installed at the site. The RTU will allow for remote data collection and system control while also providing information necessary for modeling the hybrid power system. The information from the RTU can be processed using the model described in this paper. In this way the RTU and the model can be used to optimize the performance of the hybrid power system.

2. HYBRID POWER SYSTEM MODEL

2.1 General Model

When two or more different sources of electricity are connected to a common grid and operate hand-in-hand to supply the desired load, the system becomes a hybrid power system. A simple block diagram of a hybrid power system is shown in Fig. 1.

The sources of electric power in this hybrid system consist of a diesel generator, a battery bank, a PV array and a wind generator. The diesel generator is the main source of power for many of the remote villages in Asia [1] and around the world. The output of the diesel generator is regulated AC voltage, which supplies the load directly through the main distribution transformer.

The battery bank, the PV array and the wind turbine are interlinked through a DC bus. The RTU regulates the flow of power to and from the different units, depending on the load. The integration of a RTU into a hybrid power system is important to enhance the performance of the system [10]. The overall purpose of the RTU is to give knowledgeable personnel the ability to monitor and control the hybrid system from an external control center. Since the hybrid systems of interest in this research are located in remote areas, the ability for external monitoring and control is of utmost importance. The RTU is interfaced with a variety of sensors and control devices located at key locations within the hybrid system. The RTU processes the data from these sensors and transmits it to a control center. In addition, the RTU is also capable of receiving control signals and adjusting parameters within the system without the physical presence of the operating personnel. A more in-depth description of the RTU communications as well as the unit’s importance to the modeling process is described in more detail in the next section.

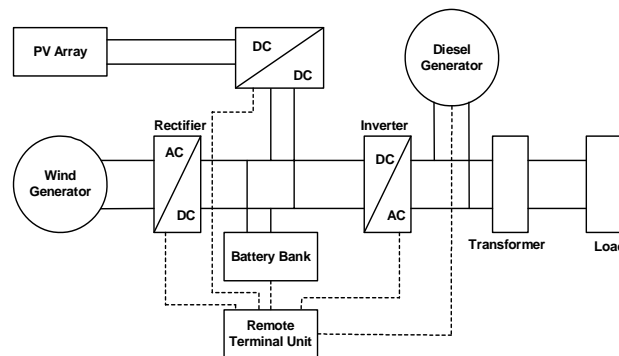


Fig. 1 General hybrid power system model

2.2 Lime Village Model

Efforts are already underway to build hybrid electric power systems in remote villages of Alaska. This paper investigates the integration of a PV array with a diesel-battery hybrid electric power system located in Lime Village, Alaska. The hybrid power system of Lime Village consists of 21 kW and 35 kW diesel generators, 100 kW-hrs of valve regulated lead acid batteries with 95, 2.2-volt cells connected in series and a 12 kW photovoltaic (PV) array. Wind generation is not a viable renewable energy source for Lime Village due to the low wind speeds in this area. A 30-kVA bi-directional power converter/controller is used to supply power to and from the batteries and PV array. Figures from the Alaska Energy Authority (AEA) show that the operating cost of fuel supplied for the generators of Lime Village ranges from \$2.80/gallon in summer to \$4.80/gallon in winter [4]. Due to the high cost of fuel, it is desired that the diesel generators operate efficiently and economically. The use of renewable energy in the form of a PV array combined with regulated battery storage helps in constraining the use of the diesel generator while optimizing the efficiency and economics of the system. Efforts are already under way to install a RTU at Lime Village, further enhancing the performance of the system.

3. SIMULATION MODEL

A model of a hybrid power system of Lime Village was designed using MATLAB™ Simulink. The overall block diagram of the current system is shown in Fig. 2. The model consists of nine different subsystems contained in blocks. The *Input Parameters* block includes data files obtained from the site. After the installation of the RTU the model will acquire the data directly from the RTU.

Sensors on the system are used to gather information such as the amount of sunlight incident upon the PV arrays, charge level of the batteries, and important operating parameters of the diesel generator. The voltage or current signals from these sensors are transmitted to signal conditioning devices that convert the signals to an instrumentation level. These signals are then passed to analog input modules of the RTU and digitized for processing. The processing consists of scaling the inputs and converting them to a meaningful unit. The data is then saved within the memory of the RTU and unloaded to a database on a central server at a location outside of the village at a user specified time-interval. The data is transferred through TCP/IP connections and is usually accomplished through dial-up/ethernet connections with the RTU. At this point the data is placed in a database and accessed via a web page or other methods and is available as input to the model [11]. This data can also be used by the system operator to evaluate the performance of the system and to make manual adjustments.

After being processed by the *Input Parameters* block of the model, this information is used by all of the other subsystems to calculate efficiency, fuel consumption, and total cost of fuel.

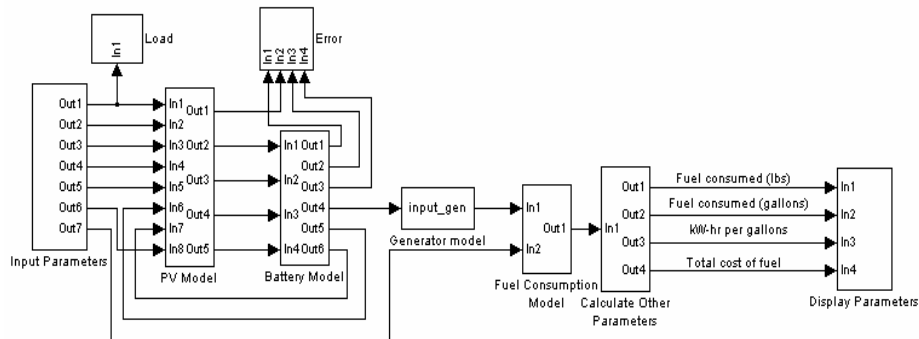


Fig. 2 Simulink model of Lime Village

The *PV Model* block is the model of the 12 kW PV array installed at Lime Village. This block calculates the power available from the photovoltaic array depending on the intensity of sunlight. The S-function written in MATLAB™ performs the following tasks:

- (1) The total voltage of the PV array is calculated using the formula,

$$pv_voltage = n_pv * v_pv \quad (1)$$

where, n_pv is the number of cells connected in series in the PV array and v_pv is the voltage per cell obtained from the manufacturer.

- (2) The total power available from the PV array is calculated using the formula,

$$pv_power = pv_voltage * pv_current \quad (2)$$

where, $pv_current$ is obtained as the input of the *PV Model* from the output of the *Input Parameters* block.

- (3) The model then compares the calculated PV power to the required load. If the PV power is more than the load on the system, the model checks the battery kW-hr. If the battery kW-hr is less than 95% of its rated kW-hr, the model will send the excess available power to charge the battery bank. On the other hand if the kW-hr rating of the battery is more than 95% of its rated kW-hr, the model will send the excess power to the dump load, which can then be utilized for space heating purposes. If the PV power is less than the load on the system, the model will supply all of the power available from the PV array to the load. The model will then use the battery bank to supply the remaining load. If the battery bank is unable to supply the rest of the load, the load is passed to the diesel generator. The diesel generator then supplies the load and charges the battery bank simultaneously.

The hybrid power system is designed in such a way that the PV array has the highest priority to supply the load. If the load is not met by the PV power, the battery bank is used to supply the required load. If the battery bank is less than 20% charged, the controller sends the signal to start up the diesel generator. The diesel generator is then used to supply the desired load and charge the battery bank simultaneously. On the other hand if there is excess power available from the PV array, the excess power is used to charge the battery bank. If the battery bank is 95% charged, the excess power is sent to a resistive dump load, which can be used for space heating purposes.

The *Battery Model* block consists of the battery bank and controller. The *Battery Model* has the second highest priority to supply the load. Once the RTU is installed at Lime Village, it will regulate the power output of the diesel generator, the PV array, and the battery bank through digital/analog output capabilities that enable equipment to be switched 'on' and 'off'. The control settings and set point configurations are programmed into the memory of the RTU. These set points of the RTU can be changed while the simulation is in progress in order to further optimize the system.

The s-function in the *Battery Model* block performs the following tasks:

- (1) The total battery voltage is calculated using the number of battery cells (n) and the voltage per cell as follows:

$$battery_voltage = n * volt_per_cell \quad (3)$$

where, $volt_per_cell$ is obtained from the output of the *Input Parameters* block.

- (2) The model then compares the required load with the maximum capacity of the two generators. If the required load exceeds the capacity of the two generators, then the model displays the message that the load cannot be supplied with the available generators. If the load is less than the maximum capacity of the two generators then, the model checks for the available kW-hr and the mode (charging or discharging) of the battery bank. If the available kW-hr of the battery bank is greater than 20% and the battery is in the discharging state, then the battery energy will be used to supply the load. If the available kW-hr of the battery bank is less than 20% of its rated kW-hr or if the battery bank is in the charging stage, then the energy from the diesel generator will be used to supply the load and charge the battery bank simultaneously.

The *Generator Model* block contains the manufacturer's specifications for the efficiency of the electric generator. Knowing the efficiency and the load on the generator, the power input to the generator can be calculated as:

$$P_{Input} = P_l * \eta \quad (4)$$

where, P_l = the load on the diesel generator.

The *Generator Model* block is designed in such a way that the diesel generators are always operating at 95% of their rated kW while operating in conjunction with the battery bank and the PV array. This way the generators operate at their maximum efficiencies and also give better displacement power factor. If one generator is insufficient to supply the load, the second generator is turned 'on'. In Lime Village one generator is always sufficient to supply the load, while the other generator acts as a back up generator. If the model is used for other villages and when there are two generators supplying the load, the percentage load on both the generators is same i.e. both the generators operate at 95% of their rated kW.

The *Fuel Consumption Model* block calculates the amount of fuel required by the diesel engine to supply the load. The fuel consumed by the engine depends on the load and the electrical efficiency of the generator. The electrical efficiency is dependent on the displacement power factor of the load. If there are two generators operating, the block will calculate the fuel required by each engine and also the total fuel required to supply the load. The plot for the fuel consumption obtained from the manufacturer's data sheet can be mathematically interpreted as follows:

$$Fuel\ consumed\ (Lbs) = 0.5 * P_{Input} + 0.5 \quad (5)$$

$$Fuel\ consumed\ (gallons) = \frac{Fuel\ consumed\ (Lbs)}{7.1} \quad (6)$$

where, P_{Input} is the input power to the generator given in kW, 7.1 is the factor that converts Pounds (lbs) to gallons depending on the type of fuel that is used. For different types of generators the fuel consumption can be obtained from the manufacturer data sheet.

The *Error block* calculates the difference between the supplied power and the required power. The error factor within the model is calculated by,

$$Error\ power = P_B + P_G + P_{PV} - P_L - P_D \quad (7)$$

where, P_B = the power supplied by the battery bank,

- P_G = the power supplied by the diesel generators,
 P_{PV} = the power supplied by the PV array,
 P_L = the power delivered to the load, and
 P_D = the power delivered to the dump load.

The block also calculates the root mean square (RMS) value of the error power. The RMS value of the error will depend on the time interval over which the simulation is performed, the time increment between the two simulation steps and the fluctuation in load. The RMS value of error is given by

$$Error\ power\ (rms) = \sqrt{\frac{\sum (Instantaneous\ value)^2}{n}} \quad (8)$$

where, n = the ratio of the simulation time to the time increment between the two simulation steps.

The *Calculate Other Parameters* block calculates the parameters such as the total kW-hrs/gallon supplied by the generator, fuel consumed in pounds and gallons, and the total cost of fuel (USD).

$$kWhrs/gallon = \frac{kWhr_{Gen}}{F_C} \quad (9)$$

$$Total\ cost\ (USD) = F_C * cost/gallon \quad (10)$$

- where, $kWhr_{Gen}$ = the total kW-hr supplied by the diesel generator, and
 F_C = the total fuel consumed (gallons).

The *Display Parameters* block is used to display all the calculated parameters including the fuel consumption, the total cost of fuel, and the kW-hrs/gallon.

After the installation of RTU, the RTU will acquire information from the sensors installed on different system components. This data will then be saved into a database. The *Input Parameters* block will acquire all the required data directly from the database. Once the data is processed by the *Input Parameters* block, the RTU will direct the data to the other subsystems for calculating electrical efficiency, fuel consumed, total cost of fuel, and the kW-hr per gallon of fuel consumed. The RTU will also regulate the flow of power to and from the different units depending on the load. Thus, the RTU will play a vital role in the overall performance of the hybrid power system.

The 24-hour summer load profile, obtained from the data acquisition system currently installed at Lime Village, is used to study the performance of the hybrid power system using the Simulink model. A 24-hour summer load profile is shown below in Fig. 3. It was recorded at Lime Village from 6:38 AM on July 11th, 2002 to 6:28 AM on July 12th. Each data point represents an average of 10-minutes of collected data.

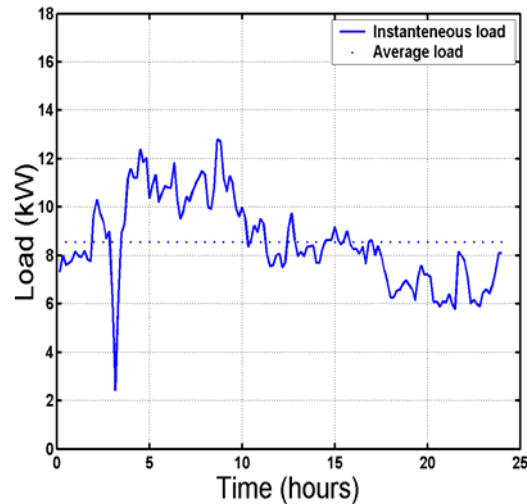


Fig. 3 24-hour summer load profile for Lime Village

Three different scenarios were tested. In case 1 the simulations were performed using only the diesel generator, without the battery bank and the PV array. In case 2 the simulations were performed using a diesel-battery combination. In case 3 the simulations were performed with the PV array integrated into the diesel-battery system that was used in case 2. In case 3 the PV has the highest priority to supply the load, with the battery bank having the second highest priority. If the battery bank is incapable of supplying the load, the diesel generator is used to supply the load and charge the battery bank simultaneously.

4. SIMULATION RESULTS AND DISCUSSION

After performing the simulation for the three cases, it was observed that case 3 provided superior results in terms of fuel consumption of the diesel generator. In case 1 the entire load was supplied without the PV array and the battery bank, leaving the load to be supplied by the diesel generator. In case 2, when the battery bank is discharged, the diesel generator is used to charge the battery bank, so eventually the entire load is met with the help of the diesel generator. In case 3, part of the load was supplied using a PV array. As a result there is substantial saving in the fuel consumption by the diesel generator due to introduction of the battery bank and the PV array with the diesel-only system.

The plot for the PV power for the summer load profile of Lime Village is shown in Fig. 4(a). It can be observed that during summer days there is abundant sunlight, hence the energy available from the sun is distributed throughout the day. Fig. 4(b) shows the plot for the power supplied to the resistive dump load. Since the dump load is 'zero' throughout the simulation period, all the extra power available from the PV array is utilized to charge the battery bank.

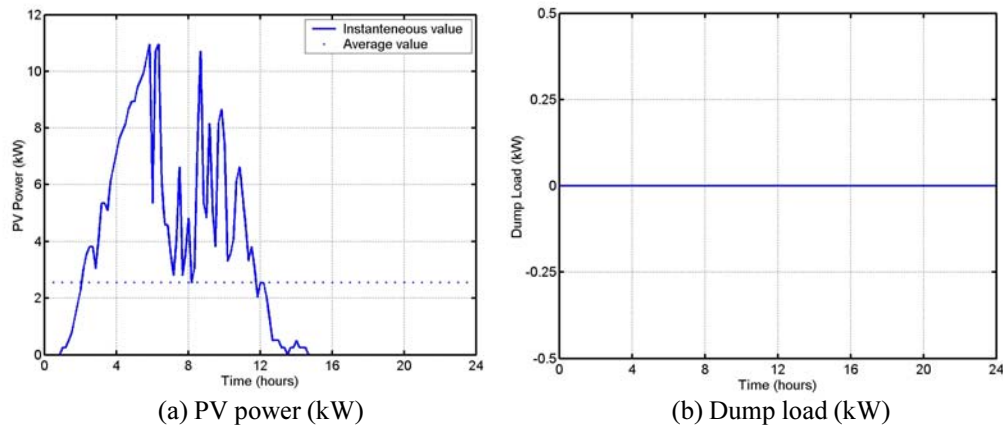


Fig. 4 24-hour: (a) PV power and (b) Dump load for the PV with diesel-battery system for summer load profile of Lime Village

The plot for the battery current and the battery kW-hr for the summer load profile of Lime Village is shown in Figs. 5(a) and (b). The negative current indicates that the battery bank is charging. It can be observed that, when the battery bank is discharging, the magnitude of current with PV incorporated is less. Since the PV array is supplying part of the load in case 3, the battery bank supplies a lower portion of the load in case 3 as compared to case 2. Therefore, the batteries can supply their portion of the load for a longer period of time with the same initial charge. As the diesel generators are running at 95% of their rated kW, there is more power available to charge the battery bank. The change of slope for a brief period of time at the simulation time of about 3.00 hrs into the simulation shown in Fig. 5(b) indicates the change in the state of the battery bank from discharge to charge. Since the power available from the PV array is more than the load on the system, the model utilizes the extra available power to charge the battery bank.

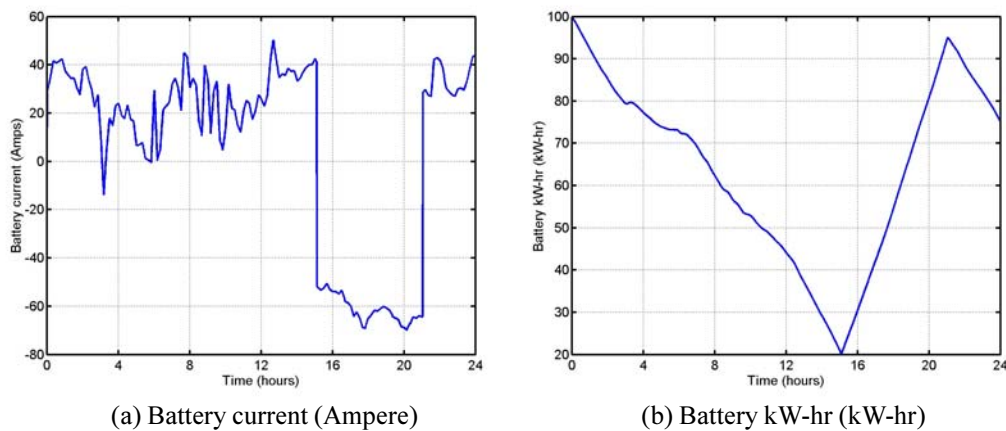


Fig. 5 24-hour: (a) Battery current and (b) Battery kW-hr for the PV with diesel-batterysystem for summer load profile of Lime Village

The plot for the electrical efficiency of the diesel generator for the summer load profile of Lime Village is shown in Fig. 6(a).

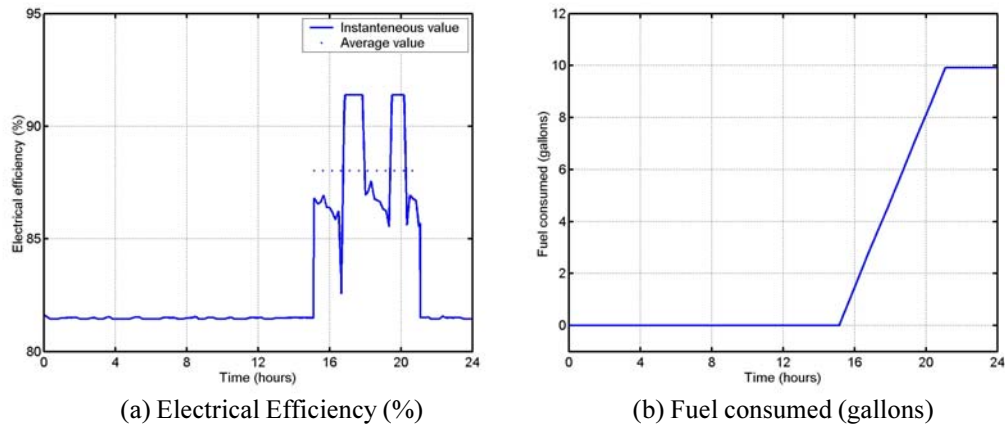


Fig. 6 24-hour: (a) Electrical efficiency and (b) fuel consumed for the PV with diesel-battery system for summer load profile of Lime Village

The electrical efficiency of the diesel generator varies between 81% and 91%. This efficiency depends on the load on the generator and the displacement power factor of the load. As the generators are operating at 95% of their rated kW, the efficiency of the generators varies with the displacement power factor of the load. Fig. 6(b) is the plot for the fuel consumed by the diesel engine for the summer load profile of Lime Village. The horizontal section in the plot indicates that the diesel engine is ‘off’ and the PV array and the battery bank are supplying the system load.

The results of the error block are shown in Fig. 7. The horizontal ‘dotted line’ in the plot indicates the RMS value of the error which is about 0.1 kW. Part of the error is due to the transfer of load between the PV array, the battery bank, and the diesel electric generator.

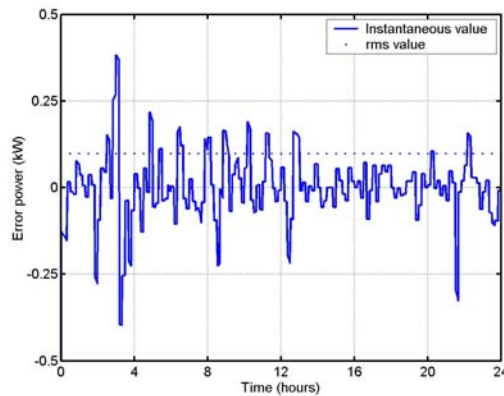


Fig. 7 24-hour Error plot for the PV with diesel-battery system and summer load profile of Lime Village

Table 1 shows the comparison of the results for Lime Village for the different cases. The various parameters considered are:

- the electrical efficiency of the diesel generator (%),
- the kW-hrs/gallon of fuel (kW-hr),
- the total fuel consumed (gallons), and
- the total cost of fuel (USD).

Table 1 Comparison of results of Lime Village for the summer load profile

Sr. No.	Item	Type of system		
		Diesel-only	Diesel-battery	PV with diesel-battery
1	Electrical efficiency (%)	86.5	88.3	88.0
2	KW-hrs/gallon of fuel (kWh)	10.22	12.01	11.96
3	Total fuel used (gallons)	20.08	17.06	11.9287
4	Total cost of fuel (USD)	80.33	68.24	47.71

As the diesel generator operates with the lowest load for the diesel-only system, it is the least efficient system. Therefore, it has the lowest kW-hrs/gallon. It was observed that the diesel-generator operates most efficiently for the diesel-battery system having the highest kW-hrs/gallon. When the PV array was incorporated into the diesel-battery system, and part of the load is supplied using the PV array, it was observed that the least amount of fuel was consumed.

5. CONCLUSIONS

The preliminary results reported here demonstrate that the integration of a PV array into a diesel-battery stand-alone hybrid power systems reduces the total fuel consumption and operating costs. Furthermore, the use of RTUs in such systems will provide designers with data for improving system models. The incorporation of additional renewable sources of energy like wind generators in this system would still further reduce the fuel consumption. It should be noted that the cost of the battery bank, the PV array and the wind generator would also play a significant role in the overall economy of the system.

The high energy demands in Asia suggest a movement towards the use of hybrid systems which combine current and emerging energy storage and renewable energy technology with conventional non-renewable energy sources like diesel generators. The use of PV power in thousands of remote communities in Asia would help to reduce the cost associated with the operation of diesel generators and the extension of the conventional grid. Hybrid energy systems which result in more economical and efficient generation of electrical energy would not only enhance the capability of automated and precision generation systems, but would also help to extend the life of non-renewable energy sources.

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