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Development of a statistical model for reliability analysis of hybrid off-grid power system (HOPS)

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ABSTRACT

The study presents a response surface (RS) model using Box-Behnken design (BBD) technique for predicting the reliability of a hybrid off-grid power system (HOPS). A three-factor three-level BBD is used to model the reliability of HOPS in terms of loss of power supply probability (LPSP). The sizes of HOPS components, namely, photovoltaic (PV) array, diesel generator (DG) capacity, and battery (BAT) cells, are the factors in the model. The effect of varying PV, DG sizes and BAT cells for the HOPS are thoroughly assessed for minimum LPSP. The analysis of variance (ANOVA) for the response (LPSP) established significant linear and quadratic terms of the RS model. The coefficients of the RS model are determined using multiple regression analysis technique at the 95% level of confidence. The RS model is verified for error in prediction by residual analysis technique and validated against experimental data to confirm the accuracy of the model. The model predicted accuracy is 97.4%. The model predicted optimum HOPS component sizes in terms of LPSP is assessed to define the energy economics of the system. The systematic approach of sizing the power sources of a HOPS in terms of supply reliability using a statistical model and subsequent validation of the prediction with experimental data taking into consideration the cost of energy generated from the system is the unique feature of the present study. The model presented in this study can be a useful tool for comparing power supply reliability of varying capacities among similar system architectures.

1. Introduction

Fossil fuels deplete and their use emits greenhouse gas (GHG) [1]. Thus, a crucial issue is to find alternative energy sources to meet the continuously increasing demand for energy while minimizing the undesirable environmental impacts. Alternative energy resources such as renewable sources have attracted energy sectors to generate power on a large scale as off-grid power sources [2,3]. However, the drawbacks of the renewable energy sources are unpredictability, meteorological dependence, and non-compatibility with the time distribution of demand. However, the solar photovoltaic (PV) is preferred across the globe as the primary renewable power source and are particularly favorable for the tropical climate. But, a standalone solar energy system cannot provide a continuous power supply due to diurnal and seasonal variations. Also, the use of single energy resource result in considerable over-sizing which hampers the energy economics [4–6].

An accepted solution is integrating multiple energy resources that are complementary to one another [7]. The integration of multiple energy sources improve the system efficiency and the reliability of the supply [8,9]. The energy system with complimentary energy sources needs to have an energy storage support, namely battery if one or more energy sources are renewable. An off-grid power system composed of single or multiple renewable options and battery storage are often economically less attractive due to the requirement of large battery bank for ensuring power reliability. The complimentary non-renewable energy sources can be particularly significant in this regard. Among the complimentary energy sources, diesel generator (DG) has been considered attractive for integration with PV in the hybrid power system. The DG involves lower capital cost, has the better accessibility of operation and simplicity of installation, however, the operation of DG is often limited due to fluctuating fossil fuel prices and environmental burden of greenhouse gas emission [10,11]. But for ensuring power supply reliability incorporation of a suitable battery bank is

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recommended for PV-DG based hybrid off-grid system (HOPS) [1,12,13].

Thus, the assessment of system reliability and sizing of the components considering the demand and resources availability is highly relevant in configuring a reliable yet economical HOPS for remote localities with PV, DG, and BAT. The present study proposes a systematic statistical approach for determining the optimal component sizes for a PV and DG based HOPS using reliability of power supply as a criterion. The loss of power supply probability (LPSP) is used to assess the reliability of power supply for the HOPS comprising of the PV array, DG and BAT [14,15]. The study aims to propose a statistical model capable of efficiently configure the component sizes for better power supply reliability and optimum utilization in a HOPS.

The design of experiments is a generic systematic statistical method used to evaluate the relationship between interacting factors. The design of experiments involve various statistical experimental design of which, the factorial design is widely used by the researchers to study the effect of multiple variables simultaneously. However, full factorial design (FFD) requires number of experiments and fractional factorial design lacks rotatability [16]. An alternate statistical approach capable to evaluate the impact of the multiple factors simultaneously in a systematic manner is response surface methodology (RSM). A well-designed RSM is also capable of optimizing multiple variables with a minimum number of experiments and can be used to establish the relationship between several independent variables and one or more dependent variables.

The RSM follows a sequential approach where the first step is to screen the independent variables (factors) and the factor levels. The second step is to define a response surface (RS) model with the selected factors and develop the experimental design for evaluation. The third step is to evaluate the response for each factor level setting of the experimental design and estimate the coefficients of the model using regression analysis technique. The fourth step is to refine the model and the final step is to assess the accuracy using experimental data. The Central-Composite design (CCD) and Box-Behnken design (BBD) are preferred experimental design for RSM based upon the desirable features of equal predictability throughout the design surface. However, the BBD is often considered more suitable for evaluating the complex response surfaces that involve second-order factor-level interactions (quadratic effect) compared to the CCD. Also, BBD requires less experiment than the CCD for the same number of factors. BBD is a three level spherical design based upon the combination of two-level factorial and incomplete block designs and therefore rotatable or nearly rotatable irrespective of the number of factors under consideration allowing to optimize the factors by a lesser number of experimental runs [16–18].

Thus, the objectives of the present study are to develop a statistical RS model using BBD to predict the power supply reliability in terms of LPSP for a HOPS comprising of PV, DG, and BAT. The sizes of components (PV, DG, and BAT) of the HOPS are considered for evaluation in a three-factor, three-level BBD to develop the RS model. Further, the RS model is to be validated and evaluated for error in prediction. The validated RS model is to be used to configure the HOPS to ensure power supply reliability and maximum component utilization. The optimum HOPS configuration is to be evaluated for the economic viability through the computation of the CoE.

This systematic approach of sizing the power sources of a HOPS in terms of supply reliability using a statistical model and subsequent validation of the prediction with experimental data taking into consideration the cost of energy generated from the system is the unique feature of the present study. The model presented in this study can be a useful tool for comparing power supply reliability of varying capacities among similar system architectures. The statistical model proposed in this study is expected to be useful in decision-making with regard to the size of power source components of a HOPS and determine the impact on the users with respect to reliability and economics.

2. System description

2.1. Site information and load data

The actual load or energy demand of a remotely located model site in north-eastern India (latitude: 23.80 N and longitude: 91.50 E) is used in this study. The average monthly clearness index is 0.54 ± 0.11 and average monthly solar irradiation is 4.83 ± 0.7 kWh/m^2/day. The daily load of the model site varies from 19.04 kW to 57.63 kW, with an annual average load of 850 kWh/day.

2.2. Energy sources

The solar energy is the primary renewable energy source for the considered model site. The geographical location of the site restricted accessibility to other renewable energy sources, hence PV is the only renewable source considered. The rated capacity of each PV module used in the study is 0.2 kW, and the efficiency of each module is 10–15% of rated power with an area of 3.66 m^2. The considered lifetime of the PV array is 25 years. The PV module converts the sunlight directly into electricity. Thus the power output of PV (P_{PV}) is calculated using Eq. (1),

$$P_{PV} = N \times E_{PV} \times \eta_{PV} \tag{1}$$

where, N is the number of PV modules, E_{PV} is the rated power and η_{PV} is the efficiency of PV module [19]. The efficiency of each module is considered 10–15% of the rated power.

Since PV is the sole energy source available for the remote site, so a conventional DG is added as a complementary source in the HOPS to meet the demand of the site. The power output of the DG (P_{DG}) is computed using the rated power (E_{DG}) and efficiency (η_{DG}), by Eq. (2) [20].

$$P_{DG}(t) = E_{DG}(t)^*\eta_{DG} \tag{2}$$

Theη_{DG} is fixed at 90% and the DG is considered to have a life of 15000 operating hours. The diesel fuel price for the operation of DG is maintained 1.25 $/L considering the fluctuation of diesel price throughout the project lifetime and is calculated according to Eq. (3) ([21,22]).

$$\textit{Diesel fuel price} = 0.0008265^*(Year)^2 - 3.2798145^*(Year) + 3253.90407 \tag{3}$$

The BAT storage is composed of 6 V, 1156 Ah cells with round trip efficiency of 80%. The minimum lifetime of the BAT bank is considered as 5 years. The state of charge of BAT ($SOC_{BAT}(t)$) is a measure of the level of stored power in the BAT at any time (t), which varies from maximum (SOC_{MAX}) to minimum (SOC_{MIN}) allowable state of charge. The value of SOC_{MAX} and SOC_{MIN} are maintained invariant at 1 (100%) and 0.4 (40%). Mathematically the constraints of the battery operation can be expressed as Eq. (4) [23],

$$SOC_{MIN} \le SOC_{BAT}(t) \le SOC_{MAX} \tag{4}$$

A converter (CONV) is added as a system component to maintain the flow of energy between the AC and DC components and thereby stabilize the system. A CONV is considered to work as an inverter