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Operation cost minimization of photovoltaic–diesel–battery hybrid systems

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ABSTRACT

In this paper, two control strategies involving “continuous” and “ON/OFF” operation of the diesel generator in the solar photovoltaic–diesel–battery hybrid systems are modeled. The main purpose of these developed models is to minimize the hybrid system's operation cost while finding the optimal power flow considering the intermittent solar resource, the battery state of charge and the fluctuating load demand. The non-linearity of the load demand, the non-linearity of the diesel generator fuel consumption curve as well as the battery operation limits have been considered in the development of the models. The simulations have been performed using “fmincon” for the continuous operation and “intlinprog” for the ON/OFF operation strategy implemented in Matlab. These models have been applied to two test examples; the simulation results are analyzed and compared to the case where the diesel generator is used alone to supply the given load demand. The results show that using the developed photovoltaic–diesel–battery optimal operation control models, significant fuel saving can be achieved compared to the case where the diesel is used alone to supply the same load requirements.

1. Introduction

The lack of reliable electrical power supply, the high cost of AC grid extension and rough topography are some of the severe challenges faced in the rural electrification of a good number of developing countries. In most of the cases, loads in those rural areas are powered by small DGs(Diesel Generators) running continuously [11]. Compared to other supply option such as renewable energy sources, DGs have low initial capital costs and generate electricity on demand. They are easily transportable, modular, and have a high power-to-weight ratio. DGs can also be integrated with other sources and energy storage in hybrid system configurations making it an ideal option for standalone power generation. However, due to the long running times and the highly non-linearity in the daily load demand profiles, DGs are usually operated inefficiently resulting in higher cost of energy produced.

The global warming, the ozone layer's depletion and other environmental impacts from using DGs (or other fossil fuels) have led to the use of RE (renewable energy) sources [13].

RE generation such as solar PV (photovoltaic) are gaining consideration, due to advantages such as low operation and maintenance, and easy deployment to meet growing energy needs [1,5,9]. Solar PV technology is an established clean way of generating energy and is currently extensively to supply power in several standalone applications [3,16,19].

However, except for its high capital cost, the other main disadvantages of PV generation is the fact that the power produces depends on the solar resources which is highly non-linear and varies with the hours of the day and the seasons of the years. Therefore the PV cannot always match the load power demand.

Hybrid solar PV–diesel–battery hybrid systems present a resolution to the time correlation of intermittent solar source as well as load demand fluctuations [4,14]. In this configuration, the DG is used to balance the deficit of the power supply from the PV and the battery when the load demand is high. This combination enhances the efficiency and the output capability of the entire hybrid system.

Several authors have discussed the optimal operation control of hybrid PV–diesel–battery systems for standalone power generation [6]. Have developed the HOGA program (Hybrid Optimization by Genetic Algorithms) used to design a PV–Diesel system (sizing and operation control of a PV–Diesel system). The program has been developed in C++. Two algorithms are used in HOGA. The main algorithm obtains the optimal configuration of the hybrid system, minimizing its Total Net Present Cost. For each vector of the

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main algorithm, the optimal strategy is obtained (minimizing the non-initial costs, including operation and maintenance costs) by means of the secondary algorithm. In the paper, a PV–Diesel system optimized by HOGA is compared with a standalone PV system that has been dimensioned using a classical design method based on the available energy under worst-case conditions. HOGA is also compared with a commercial program for optimization of hybrid systems such as the HOMER (Hybrid Optimization Model for Energy Renewable) and HYBRID2. In Ref. [7]; the same authors have presented a study of the influence of mathematical models in the optimal design of PV–Diesel systems. For this purpose, HOGA has been used. The mathematical models of some hybrid system elements have been improved in comparison to those usually employed in hybrid systems' design programs. Furthermore, a more complete general control strategy has been developed, one that also takes into account more characteristics than those usually considered in this kind of design.

Nafeh [15] developed and applied an operational control technique, based on using the FLC (fuzzy logic controller) and the commonly used ON–OFF controller for a Photovoltaic–Diesel–Battery hybrid energy system. This control technique aims to reliably satisfy the system's load, and at the same time to optimize the battery and diesel operation under all working atmospheric conditions. The proposed hybrid energy system is modeled and simulated using MATLAB/Simulink and FUZZY toolbox. The FLC is mainly designed to overcome the non-linearity and the associated parameters variation of the components included in the hybrid energy system, therefore yielding better system's response in both transient and steady state conditions.

Woon et al. [23] reviewed an optimal control approach used by Ref. [22] to evaluate the differences in operating strategies and configurations during the design of a PV–diesel–battery model. However Ref. [22], did not capture all realistic aspects of the hybrid power system. In this paper, the optimal control model was analysed and compared with three different simulation and optimization programs. The authors proposed several improvements to the current model to make it more representative to real systems.

Ashari and Nayar [2] presented dispatch strategies for the operation of a PV–diesel–battery hybrid power system using 'set points'. This includes the determination of the optimum set points values for the starting and stopping of the diesel generator in order to minimize the overall system costs. A computer program for a typical dispatch strategy has been developed to predict the long-term energy performance and the life cycle cost of the system.

Tazvinga et al. [20] developed a hybrid system model incorporating photovoltaic cells and diesel generator in which the daily energy demand fluctuations for different seasonal periods of the year in order to evaluate the equivalent fuel costs as well as the operational efficiency of the system for a 24 h period. The results show that the developed model can give a more realistic estimate of the fuel costs reflecting fluctuations of power consumption behavior patterns for any given hybrid system.

Unlike the above-mentioned papers, the present work looks at the optimization of the daily operation cost of hybrid PV–diesel–battery systems from an energy efficiency point of view, as one of the main attributes of energy efficiency is seeking for optimality. Energy efficiency can be defined as the ratio of the output to the input energy and is characterized by the performance efficiency, the operation efficiency, the equipment efficiency, and the technology efficiency as main components [25]. Operation efficiency is a system-wide measure, which is assessed by taking into consideration the optimal sizing and matching of all system components, time control and human coordination [24]. Operation efficiency can be enhanced using mathematical optimization and optimal control techniques [24,25].

Therefore, the present paper focuses on the development of two models namely the "continuous" and "ON/OFF" control strategies to minimize the operation cost of PV–diesel–battery hybrid systems during a 24 h period. Considering a short time horizon, the battery and PV's operation costs are negligible, therefore only the fuel cost of the DG is considered. The non-linearity in the fluctuation of the solar resource and the load demand, the non-linearity of the diesel generator fuel consumption curve as well as the battery operation limits have been considered in the development of the models. The simulations of two control strategies have been performed under the summer and winter load and weather conditions; the results have been compared with the case where the DG is used alone to supply the load demands.

2. Hybrid system components description and operation

The power flow of the proposed PV–diesel–battery hybrid system is shown in Fig. 1. The load demand is primarily met by the sum of the PV and the battery starts discharging within its operating limits as soon as the PV do not meet the demand. If the PV output power is above the load demand, the excess of power is used to recharge the battery. The DG is used when the power from PV and the battery cannot respond to the load energy requirements. Depending on the operation strategy selected, the DG can only supply the deficit of power needed by the load or even at the same time recharge the battery. The mathematical models of the system's different components are presented in the subsection below:

2.1. Photovoltaic system

When light strikes a silicon, gallium arsenide or cadmium sulphide cell an electric current is generated through the photovoltaic effect [17]. The power rating of a PV panel is expressed in Wp (peak Watts) indicated at "standard test conditions" conducted at a temperature of 25 °C and irradiance of 1000 W/m^2. The output power of the solar PV system can be expressed as follows [21]:

$$P_{PV} = A_{PV} \times \eta_{PV} \times \int_{t_0}^{t} I(t) \times f(t) \times dt \quad (1)$$

where: A_{PV} is the total area of the photovoltaic generator (m^2); η_{PV} is the module efficiency; I is the hourly irradiance (kWh/m^2) and *f(t)* is the radiance density.

2.2. Diesel generator

A DG is normal diesel engine coupled to an electrical generator. DGs are usually designed in such a way that they always operate close to their power rating to achieve high efficiency; this condition can be used later as an operation constraint. With this operation strategy as well as operation constraint, the DG is expected to run at high load factors, which will result a decrease of the fuel consumption, of the Carbone footprint and increase of the DG lifespan [10].

The FC (fuel cost) is calculated for a day is given by the quadratic non-linear function below:

$$C_f \sum_{j=1}^{N} \left(aP_{DG(j)}^2 + bP_{DG(j)} + c \right) \quad (2)$$

where:

N = the number of sampling intervals within the operation range or period of the system;