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Minimum cost solution of photovoltaic–diesel–battery hybrid power systems for remote consumers

Henerica Tazvinga *, Xiaohua Xia, Jiangfeng Zhang

Centre of New Energy Systems, Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa

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Abstract

Hybrid systems present a new dimension to the time correlation of intermittent renewable energy sources. The paper considers the daily energy consumption variations for winter and summer weekdays and weekends in order to compare the corresponding fuel costs and evaluate the operational efficiency of the hybrid system for a 24-h period. Previous studies have assumed a fixed load and uniform daily operational cost. A load following diesel dispatch strategy is employed in this work and the fuel costs and energy flows are analysed. The results show that the photovoltaic–diesel–battery model achieves 73% and 77% fuel savings in winter and 80.5% and 82% fuel savings in summer for days considered when compared to the case where the diesel generator satisfies the load on its own. The fuel costs obtained during both winter and summer seasons for weekdays and weekends show substantial variations which should not be neglected if accurate operation costs are to be achieved. The results indicate that the developed model can achieve a more practical estimate of the fuel costs reflecting variations of power consumption behavior patterns for any given system.

Keywords: Optimisation algorithm; Hybrid system; Control strategy; Economic dispatch; Energy efficiency; Operation efficiency

1. Introduction

The global increase in population growth and development has led to over-dependency by many nations on energy generation from fossil fuels. At the same time, concerns about global warming and depletion of fossil fuel reserves have led many nations to turn to the exploitation of renewable energy (RE) sources. In most developing countries, the main driver for RE exploitation is access to electricity especially in remote and rural areas that are not connected to the grid. RE technologies such as solar photovoltaic (PV) generation are gaining increased importance, as they offer advantages such as little maintenance, no noise and wear owing to the absence of moving parts, absence of fuel cost, and easy expansion to meet growing energy needs (Datta et al., 2009; Hong and Lian, 2012; Agrawal and Tiwari, 2011). Solar PV generation is an established clean technology and PV-based power systems are being deployed globally to provide autonomous power for various off-grid applications (Post and Thomas, 1988; Shaahid and Elhadidy, 2008; Battisti and Corrado, 2005; Tiwari and Dubey, 2010). PV modularity is one of its major strengths as this allows the users to match PV system capacity to the desired situation. The disadvantages of PV technologies are that they are capital-cost-intensive and their sunshine-dependent output may not match the load on a daily basis. Stand-alone diesel generator (DG) sets are generally inexpensive to purchase, but expensive to operate and maintain, especially at partial loads. PV and DGs have complementary characteristics in terms of capital cost, operating cost, maintenance requirements and resource availability. In order for PV systems to meet demand completely, there is a need for backup systems

* Corresponding author. Tel.: +27 12 420 2068.
E-mail address: henerica.tazvinga@up.ac.za (H. Tazvinga).

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Nomenclature

$P_1(t)$	control variable representing energy flow from the diesel generator to the load at any hour (kW)
$P_2(t)$	control variable representing energy flow from the PV array to the load at any hour (kW)
$P_3(t)$	control variable representing energy flow from the PV array to battery at any hour (kW)
$P_4(t)$	control variable representing energy flow from the battery to the load at any hour (kW)
$P_L(t)$	control variable representing the load at any hour (kW)
T_A	the ambient temperature (°C)
NT	standard andnominal cell operating temperature conditions
A_c	the PV array area (m^2)
P_{pv}	the hourly energy output from a PV generator of a given array area (kW h/m^2)
η_R	the PV generator efficiency at reference temperature
T_R	reference cell temperature (°C)
T_C	the cell temperature (°C)
I_B	the hourly global irradiation (kW h/m^2)
I_D	the hourly diffuse irradiation (kW h/m^2)
R_B	the ratio of beam irradiance incident on a tilted plane to that incident on horizontal plane
SOC	the state of charge
$B_C(t)$	the state of charge of the battery bank at any hour
$B_C(t-1)$	the state of charge of the battery bank at the previous hour
η_C	the battery charging efficiency
η_D	the battery discharging efficiency
$B_C(0)$	the initial state of charge of the battery
$B_C^{\min}$	the minimum allowable battery bank capacity (kW h)
$B_C^{\max}$	maximum allowable battery bank capacity (kW h)
DOD	the depth of discharge
a,b	fuel cost coefficients
P_{DG}	generator rated power output (kVA)

such as DGs and battery storage in a hybrid system. Hybrid systems present a resolution to the time correlation of intermittent RE sources (Muselli et al., 1999; Belfkira et al., 2011; Tiwari and Dubey, 2010). The fact that the hourly solar radiation incident on the PV module at a given location is a function of the day and time of the year means that the fraction of the load supplied by PV is not constant. This implies that in the hybrid system considered in this paper, the solar fraction and battery bank capacity are expected to have a great impact on the DG fuel consumption, depending on the day, season and load profile. A high solar resource output will result in reduced fuel consumption, as the PV will be able to generate enough power to serve the load and/or charge the battery.

Various authors have proposed hybrid PV-diesel- battery systems for off-grid applications in which the cost of energy is the main criterion used to select the optimal power system (Shaahid and Elhadidy, 2008; Dufo-Lopez and Bernal-Augustin, 2005). The selection and sizing of components of a hybrid power system in Shaahid and Elhadidy (2008) are done using the Hybrid Optimisation Model for Electric Renewables (HOMER) software developed by the National Renewable Energy Laboratory, USA. HOMER is a simplified optimization model that can perform many hourly simulations in order to come up with the best possible matching between supply and demand to design the optimum system. It uses life cycle cost to rank different systems and also calculates the annual diesel costs. The main algorithm used by Dufo-Lopez and Bernal-Augustin (2005) obtains the optimal configuration of PV panels, batteries and DG, minimizing the total net present cost of the system, which includes all the life cycle costs throughout the useful lifetime of the system. It is shown in this work that the minimum output power of the DG and the minimum state of charge (SOC) of the batteries have an influence on the total net present cost and the optimal dispatch strategy. The PV-diesel-battery systems are found to be economically better than PV or diesel stand-alone systems for peak load profiles.

An economic analysis and environmental impact model of a PV with a diesel–battery system is proposed by Wies et al. (2005), in which the fuel cost is calculated over a one-year period and simple payback is worked out for the PV module. The electric power sources in the hybrid system consist of a PV array, a battery bank, a DG, and a wind generator. The model calculates the annual cost of electricity for different systems and also the annual cost of fuel. The results show that the PV–diesel–battery hybrid power system reduces the operating costs and the greenhouse gases, as well as the amount of particulate matter emitted to the atmosphere. However, the work done by Shaahid and Elhadidy (2008); Dufo-Lopez and Bernal-Augustin (2005); Wies et al. (2005) assumes a constant load and also a uniform daily operational cost, which does not reflect the variation of radiation output throughout the year and also the varying consumption patterns.

In contrast to the above-mentioned work on hybrid systems, the current work focuses on the minimization of the