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Optimal scheduling for distributed hybrid system with pumped hydro storage

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ABSTRACT

Photovoltaic and wind power generations are currently seen as sustainable options of in rural electrification, particularly in standalone applications. However the variable character of solar and wind resources as well as the variable load demand prevent these generation systems from being totally reliable without suitable energy storage system. Several research works have been conducted on the use of photovoltaic and wind systems in rural electrification; however most of these works have not considered other ways of storing energy except for conventional battery storage systems. In this paper, an energy dispatch model that satisfies the load demand, taking into account the intermittent nature of the solar and wind energy sources and variations in demand, is presented for a hybrid system consisting of a photovoltaic unit, a wind unit, a pumped hydro storage system and a diesel generator. The main purpose of the developed model is to minimize the hybrid system's operation cost while optimizing the system's power flow considering the different component's operational constraints. The simulations have been performed using "fmincon" implemented in Matlab. The model 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 control model for the proposed hybrid system, fuel saving can be achieved compared to the case where the diesel is used alone to supply the same load patters.

1. Introduction

Stability and reliability are main requirements for industrial and domestic power supply. Sometimes, these requirements are not easily achievable due to the remote location of the demand or due to the weak grid supply. Critical loads need to be supplied with power from in-plant generators either to complement the grid or as an emergency source which can tolerate very little or no interruptions. Diesel generators (DGs) are useful in these circumstances because of their simplicity and ease of maintenance. They can be started easily without external supply assistance, available in variety of ratings [1]. DGs can also be integrated with renewable energy sources (RE) such as solar photovoltaic (PV) and wind turbines (WT), making the combination ideal for isolated power generation [2].

Hybrid solar PV–WT–diesel systems present a resolution to the time correlation of intermittent solar source as well as load demand fluctuations [3]. In this configuration, the DG is used to balance the deficit of the power supply from the renewable sources and the battery system when the load demand is high. This combination enhances the efficiency and the output capability of the entire hybrid system [4].

Energy storages are one of the few responses to the integration with variable energy production due to the fluctuation of their resources [5]. Storage system can decrease the effects of variable output power from renewable energy sources, and assure that power can be reliably dispatched in response to the fluctuating load requirements [6]. At this present time, PHS is the most widespread energy storage system not dealing with the conversion of chemical energy to electricity. This technology can be implemented with a roundtrip efficiency of 70–80%, and its capacity is not influenced by the seasonal variation of the water flow [7].

Currently, the development of models for optimal scheduling and energy management of standalone or grid connected renewable systems is gaining attention as a way to minimize the operation cost of hybrid systems. Several papers have discussed the optimal operation control of hybrid renewable energy sources with diesel systems for isolated power generation, but very few considered PHS as energy storage system.

In Ref. [8], two control strategies involving 'continuous' and 'ON/OFF' operation of the diesel generator in a PV–diesel–battery hybrid system have been modeled and used to demonstrate the

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Nomenclature

Abbreviations

DG	diesel generator
HKT	hydrokinetic turbine
PHS	pumped hydro storage
PV	photovoltaic
WT	wind turbine

Symbols

δ	evaporation and leakage loss
η_{DG}	diesel generator efficiency
η_{M-P}	overall pumping efficiency
η_{T-G}	overall efficiency of the turbine–generator set
ρ_a	air density (kg/m^3)

Subscripts

A	turbine area (m^2)
$C_{p,HKT}$	coefficient of the wind turbine performance
E_{DG}	energy from the diesel generator (kW h)
E_{PV}	energy from the photovoltaic system (kW h)
E_{WT}	energy from the wind generation system (kW h)
E_{Load}	load energy demand (kW h)
E_{M-P}	charging energy from the hydrokinetic system to the pump (kW h)
E_R	potential energy of the water stored in the upper reservoir (kW h)
E_{T-G}	energy generated from the turbine–generator (kW h)
g	gravity (m/s^2)
h	net pumping head (m)
j	sampling interval considered (s)
N	number of sampling intervals
P_{DG}	power from the diesel generator (kW)
P_{PV}	power from the photovoltaic system (kW)
P_{WT}	power from the wind generation system (kW h)
P_{Load}	load energy demand (kW)
P_{M-P}	charging power from the hydrokinetic system to the pump (kW)
P_{T-G}	power generated from the turbine–generator (kW)
Q_{M-P}	water flow rate from the pump (m^3/s)
Q_{T-G}	water volumetric flow rate from the reservoir onto the turbine (m^3/s)
t	time (s)
V	storage capacity of the water reservoir (m^3)
v_a	wind current velocity (m/s)

cost effective character of the proposed system compared to the DG alone. In Ref. [9], the author has taken the study further by adding a WT to the PV–diesel–battery hybrid system proposed in Ref. [8]. In Ref. [10], the optimal energy management of a more comprehensive system composed of a hydrokinetic (HKT) in combination with PV, WT, DG and battery storage system has been studied under different loads and weather conditions with the aim of minimizing the operation cost. In Ref. [11], an optimal energy management model of a PV, DG–battery hybrid power supply system for off-grid applications is presented. The proposed model minimizes fuel and battery wear costs and finds the optimal power flow, taking into account photovoltaic power availability, battery bank state of charge and load power demand.

In Ref. [12], an optimization model for the operation of a hybrid energy system consisting of a hydrokinetic system, a battery bank and diesel generator is developed. The optimization approach is aimed at minimizing the cost function subject to the availability of water resource, total load energy requirements as well as the diesel generator and the battery operational constraints. The effect of using a PHS instead the battery bank, in the system studied in Ref. [12], has been investigated in Ref. [13].

Based on the potential benefits of decentralized energy sources and storage systems in rural electrification as exposed in the different research discussed in the sections above, the combination of hybrid renewable energy systems with PHS is proposed in the present study. This arrangement can be seen as an attractive and interesting alternative for isolated power generation and storage problems with several benefits such as lowered cost of energy produced; lowered environmental impacts and increased reliability and availability of the electrical power supply.

Therefore, this paper develops a model to optimize the daily operation of a system consisting of a PV, WT, DG and PHS. The optimization approach aims at minimizing the operation cost function subject to the load energy requirements as well as to the operational constraints of the hybrid system's components. Considering a short time horizon, the PV, WT and PHS's daily operation costs are not taken into account, thus only the cost of the DG's fuel consumed is considered. Therefore, the main purpose of the developed control algorithm is to minimize the DG's operation cost while maximizing the use of PV, WT and PHS in the electricity generation process.

The main contribution is the consideration of PHS in the architecture of the proposed system, as PHS can have a great impact on the hybrid system's operation cost and environmental impacts; and these have not been considered in the optimization of renewable energy based distributed hybrid systems.

2. Hybrid system's components and operation description

The power flow of the proposed PV–WT–DG–PHS system is shown in Fig. 1. The load energy requirement is principally covered by the PW and WT units. When there is more than enough energy to supply the load directly from the PW and WT units, the surplus of generated energy is used to drive the motor–pump set to fill-in the upper reservoir of the PHS. However, when there is an insufficient energy to supply the load directly from the PW and WT units, the extra energy is provided from the water flowing down from the PHS's upper reservoir and driving the turbine–generator set. If the PW and WT units and the turbine–generator set from the PHS cannot respond to the load energy requirement, the DG is turned on as a last resort, in order to balance the shortage of energy needed by the load. The flowchart illustrating the simulation and optimization procedure is presented in Fig. 2.

2.1. Photovoltaic system

Solar panels convert light into electrical energy through the photovoltaic effect [14]. The output power of the solar PV system can be expressed as follows [15]:

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

where A_{PV} is the total area of the photovoltaic generator (m^2); η_{PV} is the system's efficiency; I is the hourly irradiation (kW h/m^2) and $f(t)$ is the radiance density.