Energy Conversion and Management 126 (2016) 446–462

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Optimised operation of an off-grid hybrid wind-diesel-battery system using genetic algorithm

Leong Kit Gan *, Jonathan K.H. Shek, Markus A. Mueller

Institute for Energy Systems, School of Engineering, The University of Edinburgh, The King's Buildings, Mayfield Road, Edinburgh EH9 3DW, UK

ARTICLE INFO

Article history:
Received 19 March 2016
Received in revised form 18 July 2016
Accepted 23 July 2016

Keywords:
Hybrid wind-diesel-battery system
Off-grid
Optimisation
Operational research
Genetic algorithm
Renewable energy
Modelling
Dynamic analysis

ABSTRACT

In an off-grid hybrid wind-diesel-battery system, the diesel generator is often not utilised efficiently, therefore compromising its lifetime. In particular, the general rule of thumb of running the diesel generator at more than 40% of its rated capacity is often unmet. This is due to the variation in power demand and wind speed which needs to be supplied by the diesel generator. In addition, the frequent start-stop of the diesel generator leads to additional mechanical wear and fuel wastage. This research paper proposes a novel control algorithm which optimises the operation of a diesel generator, using genetic algorithm. With a given day-ahead forecast of local renewable energy resource and load demand, it is possible to optimise the operation of a diesel generator, subjected to other pre-defined constraints. Thus, the utilisation of the renewable energy sources to supply electricity can be maximised. Usually, the optimisation studies of a hybrid system are being conducted through simple analytical modelling, coupled with a selected optimisation algorithm to seek the optimised solution. The obtained solution is not verified using a more realistic system model, for instance the physical modelling approach. This often led to the question of the applicability of such optimised operation being used in reality. In order to take a step further, model-based design using Simulink is employed in this research to perform a comparison through a physical modelling approach. The Simulink model has the capability to incorporate the electrical and mechanical (Simscape) physical characteristics into the simulation, which are often neglected by other authors when performing such study. Therefore, hybrid system simulation models are built according to the system proposed in the work. Finally, sensitivity analyses are performed as a mean of testing the designed hybrid system's robustness against wind and load forecast errors.

1. Introduction

The concept of off-grid hybrid renewable energy systems are known as an attractive and sustainable solution for supplying clean electricity to autonomous consumers. Typically, this applies to communities that are located in remote or islanded areas where there is no connection to the main grid infrastructure and it is not cost-effective to extend the grid facilities to these regions. In addition, the use of diesel generators for electricity supply in these remote locations are proven to be high cost due to the difficult terrain which translates into high fuel transportation costs [1]. In addition, the carbon footprint of energy is also proven to be higher for the case of diesel-only solution [2]. A techno-economic study based on the rural areas in Sub-Saharan Africa has shown that the levelised cost of electricity (LCOE) of an optimised hybrid renewable energy system is lower than the LCOE obtained with standalone diesel generators [3]. The use of renewable energy sources coupled with the diesel generator allows for the cost of diesel fuel to be offset. However, to date, a common design standard for an off-grid system has yet to be found and the challenge in power dispatch strategy still exist while attempting to optimise the operation of an off-grid hybrid system. Moreover, the challenges increase disproportionately when multiple assets are combined. It is well-known that a diesel generator is recommended to operate at 40% of its rated capacity or higher to prolong diesel engine lifetime [4]. In addition, the continuous shifting of diesel engine between different operating states could possibly shorten its lifetime [5]. It is acknowledged that the user load profile is not constant throughout the day and it is often well below the suggested part-load diesel capacity. Furthermore, the situation becomes worse when the variability of the renewable energy sources is not taken into consideration while operating the hybrid system. The diesel generator's part loading problem can be alternatively mitigated by using a variable-speed diesel generator which was proposed in [6]. A comparison of the fuel consumption power

* Corresponding author.
E-mail address: leong.kit.gan@gmail.com (L.K. Gan).

http://dx.doi.org/10.1016/j.enconman.2016.07.062
0196-8904/

curve between a fixed-speed and a variable-speed diesel generator has been carried out in [6]. The difference in fuel consumption between the two diesel generator types is small in the lower power ranges and non-existent above 65 kW [6]. One should evaluate the loading profile carefully as to whether or not the installed variable-speed diesel generator unit is economical as it utilises power electronics and permanent magnet generator which dramatically increases the control requirements, complexity and therefore the overall cost. In this work, the fixed-speed diesel generator is given attention to mitigate the part load.

The inclusion of batteries in a hybrid wind-diesel system allows a fixed-speed diesel generator to run at full load regardless of the load demand level at any particular time. In this case, the batteries are regarded by the diesel generator as an additional load in order to increase the power output closer to its rated capacity. In windy locations, the diesel generator is only switched-on whenever there is a lack of energy from the wind and battery storage. An unknown matter in this case is the duration that the diesel generator should be operated. If a diesel generator runs for too long and charges the batteries to a high state-of-charge (SOC), the potentially available excess wind energy at a later time cannot be stored. Subsequently, excess energy is dissipated in a large dump load or wind power generation is curtailed. One way to help in matching the irregular pattern of the energy supplied from the wind to the load demand profile, is to install as much energy storage as possible. However, a hybrid system which has been designed in this manner will not be economical. This further emphasises the need to optimise the operation of a hybrid system, so that the energy storage system can be used efficiently to cope with drastic fluctuations in wind energy.

Tazvinga et al. [7] has utilised model predictive control (MPC) technique to maximise the utilisation of renewable energy while minimising the operation cost and battery's charge-discharge cycles within a hybrid photovoltaic-wind-diesel-battery system. However, the diesel generator was scheduled to operate at part load condition within the considered time-frame. In a similar study, the MPC technique was applied in optimising the energy dispatch of a hybrid photovoltaic-diesel-battery system, with the aim of reducing the diesel generator use [8]. Nevertheless, frequent diesel generator power output variations were observed from the simulated results. As shown from the case study in Dhahran (Saudi Arabia), the diesel generator fuel consumption within a hybrid system is inversely proportional to the installed battery capacity [9]. Authors in [10] have proposed a stochastic dynamic multi-stage model to optimise the diesel dispatch operation of hybrid wind-diesel-battery systems. The proposed diesel dispatch strategy was compared against the load following and full-power strategies in [11]. In order to reduce the computational burden while seeking the optimal solution of the complex model, hourly time-steps were considered. Hence, the short-term peaks in the load demand were not considered. In literature [12], an optimised hybrid system which integrates demand response schemes and day-ahead forecasting of renewable energy resources and load demand was studied. However, it is noticed that the diesel generator was frequently changing its output power throughout the day. The optimisation strategy was carried out over a moving time-horizon in order to determine the optimal power references for various energy generation sub-systems. From the hybrid system sizing point of view, the authors in [13] have utilised Genetic Algorithm (GA) to optimise the PV tilt and surface azimuth angles angle by maximising annual energy production and other hybrid system components. The optimal system was designed for remote communities in Palestine with the cost of global warming emissions being taken into consideration. An improved GA was proposed in literature [14] for the use of hybrid system power generation. Its performance was compared against the standard GA in terms of convergence speed through the formulated scenario simulations. Besides satisfying electricity demand, a hybrid system model which also provides water supply and hydrogen for automotive use is studied in literature [15]. A constrained optimal real-time operational management was presented for the case of hybrid system which integrates wind turbines, electrolyser, hydroelectric plant, pumping stations and fuel cell [15].

Despite the considerable work being carried out by the above-mentioned studies, the authors optimised their hybrid system's operation using only mathematical approach. The main drawback of this approach is the lack of mechanical and electrical considerations which take place in the real world, in particular, the physical dynamics of the system. The electrical transients which typically occur in the timescale of less than one second were not considered. In addition, most of the mathematical optimisations are performed in an hourly discretised manner, which further decrease the accuracy of the optimised results produced. For the case of larger power systems, sampling time with lower resolution is acceptable, because for instance, the total load demand and total wind power generation are aggregated from many households and wind turbines, respectively. In contrast, power fluctuations experienced by smaller power systems (in the scale of kW) can vary considerably [16]. It is known that if the day-ahead forecasted wind and load are available, the operation of the diesel generator can be optimised. A set of constraints such as the allowable range of battery SOC, the diesel generator capacity and the battery storage capacity are to be met within the optimisation problem. Other than integer programming optimisation techniques, which generate binary solutions, the solution produced by other optimisation algorithms can be of any value. However, integer programming has a restriction in which the objective function and the constraints are linear. Since it is desired to run the fixed-speed diesel generator at its rated power, the optimised solutions obtained from a non-integer programming technique need to be post-processed. This will be further described in the later sections. For the first time, this work proposes a methodology to optimise the operation of the diesel generator, by considering its efficiency and also reducing the start-stop cycles in order to safeguard its lifetime. Besides that, the author put emphasis on the electrical and mechanical considerations, through the utilisation of physical modelling after developing an optimised control solution mathematically.

The proposed simulation methodology is formulated in three steps, as presented in Fig. 1. First of all, the optimised solution is sought by optimising the diesel generator's operation using GA, based on the forecasted wind and load profiles which are discretised every 10 min. It is acknowledged that an accurate estimation of load demand and meteorological data present high cost and design complexity during its implementation stage [17]. There are several techniques to forecast short-term electricity load demand but mainly they can be classified into statistical and artificial intelligence (AI) techniques [18]. A recent AI-based load forecasting which utilised extreme learning machine theory is presented and its performance was benchmarked against traditional models such as neural networks and adaptive neuro fuzzy inference system [19]. One of the approaches to predict the very short term (10 min) wind speed is by using the k-nearest neighbour (k-NN) classification model. This model uses wind direction, air temperature, atmospheric pressure and relative humidity parameters to predict wind speed [20]. However, a recently developed long-term (24 h) forecasting wind speed model is more suitable to be used as the wind forecast input for this research if one desires [21]. Once obtaining the mathematically optimised diesel generator power dispatch strategy, it is to be processed such that the diesel generator should operate at its rated power with