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A review and technical assessment integrating wind energy into an island power system

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ABSTRACT

Integrating wind power into an existing power system poses technical challenges including optimal wind turbine selection, determining an adequate penetration level and maintaining power system stability. This study addresses these challenges for proposed sites in Trinidad and Tobago. Two wind regimes were considered, their average wind speeds extrapolated to 75 m were respectively 5.3 ms^{-1} and 9.1 ms^{-1}. A wind turbine based on computed Capacity Factors (*CF*) of respectively 28.09% and 73.29% was selected for the sites. Appropriate wind power penetration levels were determined by applying the Monte Carlo Simulation (MCS) technique to generate probabilistic indices. Wind power penetration levels of 1% (15 MW) and 2% (30 MW) of total generation capacity were considered appropriate. Transient simulations were conducted in CYMSTAB to evaluate the impact of the Wind Turbine Generator (WTG) on the power system stability. Frequency, voltage and rotor angle stability were assessed. Frequency deviations from nominal increased proportionally with the number of WTGs connected. The sites' wind speed characteristics significantly influenced the active and reactive power generation capabilities of the WTGs, impacting the voltage profile and angular separation. In all simulation cases, the power system remained stable.

Contents

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1. Introduction

Renewable sources of energy reduce the dependence on fossil fuels to generate electricity. Wind is a ubiquitous renewable resource in the Caribbean region. The wind is intermittent, diffused and unpredictable, so when Conventional Generating Units (CGUs) are replaced by Wind Turbine Generators (WTGs) it is necessary to assess the adequacy of the power system for this new mixture of generation. The Wind Energy Conversion System (WECS) may impact the dynamic stability of the network and the reliability state of the power system. The frequency, voltage and rotor angle responses of the power system must be analyzed with the integrated WECS.

In the adequacy analysis (Section 3) a model to efficiently dispatch the WTGs output is adopted. In this approach the load profile is used to regulate the amount of dispatched wind energy. The model maximally dispatches the available wind energy to complement the conventional generation in supplying the load. However, in this model surplus wind energy is curtailed. The model could be modified to include an energy system flexibility strategy to increase the amount of dispatched wind energy by preventing curtailment. Strategies may include storage or Demand Side Management (DSM). On the hours to days' timescale Electrical Energy Systems (EES) such as pumped hydro energy storage (PHES), compressed air energy storage (CAES) and sodium–sulfur (NaS) batteries may be the most economically and technically suitable for managing the variability posed by large scale renewable energy sources (RES) [1,2].

The efficiency of PHES which lies between 65–85% makes it an attractive solution, it is however limited to high power applications due to high capital costs [1]. In 2010 there were three incidents in Ireland's All-Island Grid (AIG) which resulted in wind curtailment due to wind penetrations exceeding 40% of load during low demand [3]. A rule of thumb that curtails wind in excess of 50% is considered in [4]. However Tuohy and O'Malley used a stochastic unit commitment model to show that PHES could decrease wind curtailment in the high penetration range of 34–68% [5].

In CAES plants the energy is stored in compressed air in an underground containment. The measured efficiency for a practical CAES system is reported to be 25–45% [6], when the heat losses are stored in liquid or solid form the efficiency can increase to 70–80% [6]. The Huntorf CAES plant in Germany rated 290 MW for 2 h is successfully used to level wind variability [7].

NaS batteries have a good specific energy density of 100–200 W h/kg (compare Lead-acid 20–40 W h/kg), the life time expectancy is between 10–15 years and cycling can be as high as 5000 cycles at 80% Depth of Discharge (DOD) [1,2,8]. The reported efficiency is between 75–90% [1,2,8]. However NaS batteries must be operated at high temperatures between 300 and 350 °C [1,2,8] and could have high capital costs [1,8]. Lithium-ion (Li-ion) batteries have comparable properties to NaS batteries. Reported efficiencies lie between 90 and 100%, the specific energy is in the range of 90–100 W h/kg and cycle life is the range of 500–7000 cycles at DOD of 80% [2,8]. Li-ion batteries are however still expensive for large scale integration [2]. In Japan a 34 MW NaS-battery system is used to support the integration of a 51 MW wind farm [1,2].

Curtailment of surplus wind energy can also be avoided with the use of thermal storage systems. The main technologies include electric boilers and heat pumps. Curtailed wind energy has already been used in Jilin China to replace coal-fired heating [2].

Studying the correlations between the load and RES could help decrease wind curtailment. In [9] de Jong et al. studied the correlation of renewable sources of wind, solar, hydro and the demand profile for the Northeast region of Brazil. A strong correlation was computed for the evening peak load and available wind power and suggests the wind power to be more effective in the evening hours. The study also shows that the variability of these renewable sources can be smoothed out by complementing each other.

Load shifting is found to be the most promising DSM strategy in [2] as it may provide load flexibility without compromising the functionality of the final device services and continuity of process. The study in [10,11] demonstrates that optimal control of residential load increased the wind demand. Optimal control of water heater increased wind demand by 5–26%, while a 34% increase in wind demand was obtained with optimal dishwasher control. Load shifting of Industrial loads to a low price regime was found to provide significant benefits according to [12]. The study showed that a 10% reduction in the average unit electricity price (AUP) provided an increase of 5.8% in wind demand.

In this study only the dynamic responses of the generation side are considered, however DSM may also provide countering measures to improve the dynamics of the power system. In [13] it is shown that loads could provide frequency stabilization. Sufficient rotating motor loads may provide inertial responses similar to rotating generators [14]. Short et al. [15] showed by simulation that satisfactory frequency response to sudden demand increase or generation decrease in a system with fluctuating wind can be achieved through an aggregation of frequency-responsive domestic refrigerators.

Research found in [16] analyzed the Weibull, Rayleigh and Multi-peak Gaussian probability density functions (PDFs) for 208 sites in India. The R-squared (R^2) fitness results showed that the Multi-peak Gaussian PDF provided better results to multi-modal (wind profiles with more than two optimum peaks) wind profiles than the Rayleigh and Weibull PDFs. For uni-modal wind profiles the R^2 fitness results of the Rayleigh, Weibull and Multi-peak Gaussian PDFs were similar.

In the work done by Carta et al. [17] a range of PDFs and their frequently used estimation techniques were analyzed for four different wind profiles in the Canary Islands. The study examined the complexity of the estimation techniques in relation to the goodness-of-fit to recorded data provided by each technique. The fitness of the PDFs was judged by the R^2 statistic. The variety of PDFs studied were previously proposed by other researchers and include: hybrid PDFs (mixture of PDFs) for wind profiles with null-wind speed probability, uni-modal and bi-modal wind speeds [17,18]; the inverse Gaussian PDF for sites with low frequencies of low wind speeds [19] and a singly truncated normal PDF for sites with high probabilities of null wind speeds [20]. It was found that while the Weibull PDF provided the best overall results, it cannot accurately represent all recorded wind regimes encountered, especially those with high probability of null wind speeds and bi-modality. It was concluded that the Weibull PDF has several advantages which includes flexibility, the requirement of only two parameters and simplicity of parameter estimation regardless of the estimation technique. This finding is consistent with the work found in [21].

The estimation techniques used for computing the PDF parameters were the moments method (MM), the maximum likelihood method (MLM) and the least squares method (LSM). The LSM provided the highest R^2 values for PDFs that can be linearized such as the Weibull and Rayleigh. However for other PDFs it depends on