Journal of Energy Storage 16 (2018) 76–83

Contents lists available at ScienceDirect

Journal of Energy Storage

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

Mitigation of large power spills by an energy storage device in a stand alone energy system

Debarati Bhaumik[a,*], Daan Crommelin[a,b], Bert Zwart[a,c]

[a] Centrum Wiskunde & Informatica (CWI), Amsterdam, The Netherlands
[b] Korteweg-de Vries Institute for Mathematics, University of Amsterdam, The Netherlands
[c] Department of Mathematics and Computer Science, Eindhoven University of Technology, The Netherlands

ARTICLE INFO

Article history:
Received 7 November 2016
Received in revised form 3 November 2017
Accepted 16 December 2017
Available online xxx

Keywords:
Importance function
Large power spills
Rare-event simulations
Splitting
Stochastic modeling
Storage device

ABSTRACT

The unpredictable nature of wind energy makes its integration to the electric grid highly challenging. However, these challenges can be addressed by incorporating storage devices (batteries) in the system. We perform an overall assessment of a single domestic power system with a wind turbine supported by an energy storage device. The aim is to investigate the best operation mode of the storage device such that the occurrence of large power spills can be minimized. For estimating the small probability of large power spills, we use the *splitting technique* for rare-event simulations. An appropriate *Importance Function* for splitting is formulated such that it reduces the work-load of the probability estimator as compared to the conventional Crude Monte Carlo probability estimator. Simulation results show that the *ramp constraints* imposed on the charging/discharging rate of the storage device plays a pivotal role in mitigating large power spills. It is observed that by employing a new charging strategy for the storage device large power spills can be minimized further. There exists a trade-off between reducing the large power spills versus reducing the average power spills.

1. Introduction

Integration of intermittent renewable sources of energy like solar and wind power into the electric grid has increased in recent times. The depletion of the exhaustible resources of energy and the strive for a carbon free future will enhance the usage of these renewable sources more. The unpredictable nature of the renewable energy sources lead to intermittent power generation. This makes the integration of renewable energy sources into the power grid a highly challenging task.

For stable or reliable operation of power systems the voltage and frequency of the grid should be maintained within acceptable limits. The stability should be maintained within the timescale of seconds [1]. Large scale integration of distributed variable energy sources like PV arrays and micro-generator wind turbines can jeopardize the demand and supply balance of the grid due to sudden injection or deficit of power [1,2]. An instantaneous or sudden influx of power challenges the reliability of the grid, and grid operators frequently resort to curtailment of renewable energy sources in order to maintain grid stability [3–6]. Such curtailments lead to economic losses for the involved energy producers. Therefore, it is important to minimize such sudden influx of renewable power into the grid.

To improve the practical efficiency of intermittent renewable energy and to minimize the need of drastic actions (like using expensive fast ramping generators) for ensuring reliable operations of the power grid, local storage of excess power can be an important tool. The energy storage device acts as buffer energy source. It stores energy when there is over-generation of power, and delivers the stored energy to the system when there is under-generation of power.

Stand-alone systems with renewable generations like solar photovoltaic (PV) and wind supported with battery storage has been investigated in great detail with respect to the PV-wind generation sizing, performance, battery storage sizing, efficiency, optimization, system cost and reliability indices in [7–17]. Xu et al. [18] investigated the feasibility of replacing diesel generation entirely with solar PV and wind turbines supplemented with energy storage by characterizing the load-shedding probabilities. Semaoui et al. [19] recommended a model to optimize the sizes of battery capacity and PV generator for stand-alone PV system using two optimization criteria, the loss of power supply probability

* Corresponding author.
E-mail address: bhaumik@cwi.nl (D. Bhaumik).

https://doi.org/10.1016/j.est.2017.12.012

(LPSP) reliability criterion and energetic cost for economic evaluation. Cabral et al. analyzed loss of power supply (LPS) and LPSP for sizing the PV generators of stand-alone PV systems in [20]. Billinton et al. [21] presented a simulation model for the reliability evaluation (loss of load expectation and loss of energy expectation) of small stand-alone wind energy conversion systems with respect to battery size, charging (discharging characteristics), wind speed, wind turbine characteristics, etc. Casares et al. [22] devised a mathematical methodology to predict Loss of Load Probability (LLP) for sizing stand-alone photovoltaic systems.

In this paper we focus on large power spills caused by wind power, i.e. on instances where the power generation is substantially larger than the locally consumed power so that there is a large excess. This excess of power either is lost or must be fed to the grid. The former situation leads to economic losses to the wind energy producers and the latter situation may cause problems in the grid such as voltage imbalances or current overloads. In this study we investigate a stand-alone single domestic energy system with a local micro-generator wind turbine supplemented with a battery. We aim to answer: How can we efficiently quantify the *Probability of Large Power Spills* (PLPS) for a stand alone energy system model? We present a computational methodology to do so. Using this methodology, we compare different battery switching strategies and their impact on PLPS. We analyze a single domestic household because many such households make up a part the distribution grid and an instantaneous influx of large power from geographically correlated households powered by wind can lead to severe damage to the grid. For example in January 2015 in Germany, a sudden influx of wind power cost the grid operators 13 million euros in order to keep the grid under stable operation [23]. Also, this analysis of a single household serves as a prototype for bigger systems such an energy island or a region of the grid with high penetration of renewable energy sources.

We use a simple energy balance method for the switching (charging/discharging) of the battery, i.e., when there is excess power generation the battery is charged and when there is deficit of power it is discharged. Such a simple switching strategy of the storage device has been considered in many previous studies on energy systems with renewable generations supplemented with storage devices, e.g. [15,17–25].

To this end, we devise models for simulating the wind speeds and power demand such that the invariant probability densities of the data generated by the models are comparable to the data from measurements. With these models for power generation and demand, we analyze how the *ramp constraints*, the imposed maximal charging/discharging rates on the storage device affects the probability of large power spills. We define a strategy for charging the storage device to reduce the probability of large power spills further. And finally, we study the effect of the ramp constrains and the new charging strategy on the average power spilled in a given time interval of interest. It is expected that the new scheme for charging the storage device will increase the average power spill. We find that there exists a trade-off between reducing the probability of large power spills and reducing the average power spilled by the system.

The probability of occurrence of large power spill is small. The Crude Monte Carlo (CMC) probability estimator is robust but becomes computationally expensive for small probabilities. To reduce the workload of CMC we use the *splitting technique* for rare-event simulations in our study [26]. We use a variant of the splitting technique called the Fixed Number of Successes (FNS) proposed by Amrein and Kunsch [27] for calculating the probability of large power spills. Wadman et al. used FNS to estimate electrical grid reliability in [28]. It is of great relevance to find an appropriate *Importance Function* (IF) for the splitting technique, as it plays the most significant role in the efficiency of splitting [29]. We formulate an appropriate IF for our hybrid stochastic power system described above.

In Section 2 we describe the set up of the system, the storage model, problem description and the stochastic models for power generation and demand. Section 3 provides details of the FNS splitting technique and the appropriate importance function for the problem. Section 4 presents the simulation results showing how the probability of large power spills vary with the battery parameters and charging strategy. In this section we also compare the CMC and FNS computation time. At the end Section 5 concludes the article.

2. System set up

In the single domestic power system with stochastic wind power generation and demand, a battery is incorporated as a storage device in order to reduce large power spills. Let $P(t)$ be the power mismatch between the wind power generation and demand (load) defined as

$$P(t) := W(t) - D(t), \tag{1}$$

where $W(t)$ is the wind power generated and $D(t)$ is the power demand at time t. $P(t) > 0$ implies there is excess of power in the system and can be used to charge the energy storage device and $P(t) < 0$ denotes paucity of power in the system and the storage device needs to be discharged.

2.1. The storage model

Let us consider a battery as the energy storage device in the power system. The state of the battery at time t is given by $B(t)$ and it has a maximum storage capacity $B_{\max}$. For any storage device there will be bounds on the rate at which it can be charged or discharged known as **ramp constraints** [30]. The ramp constraints are denoted as δ and β such that $\delta < 0$ and $\beta > 0$. Losses occur during charging and discharging the battery which depends on the *efficiency parameters*, α_c and α_d of the battery, where $\alpha_c, \alpha_d \in [0, 1]$. The battery is modeled according to

$$\frac{dB}{dt} = \dot{B}(t) := \left(\alpha_c \mathbb{1}_{\{P(t)>0\}} + \frac{1}{\alpha_d}\mathbb{1}_{\{P(t)<0\}}\right)P(t), \quad \text{for } t \in [0, T], \tag{2}$$

with the *battery constraints*, namely the ramp and capacity constraints imposed on it

$$\begin{aligned} &\delta \le \dot{B}(t) \le \beta \quad \text{where } \delta < 0 < \beta, \\ &0 \le B(t) \le B_{\max} \qquad \forall t \in [0, T]. \end{aligned}$$

T is the time length of 24 h. $\mathbb{1}_{\{\cdot\}}$ is the indicator function which takes value 1 if the expression in the parenthesis is realized else it takes value zero. Thus, in principle, the battery is charged when $P(t) > 0$ and discharged if $P(t) < 0$ unless the battery constraints are met.

In our computational experiments, time is discretized into $N = \frac{T}{\Delta t}$ time steps, where Δt is the time step of integration. The battery state is updated according to the Euler scheme

$$B(t+1) = \min(B_{\max}), \max(0, B(t) + \Delta B(t))), \tag{3}$$

where

$$\Delta B(t) = \min(\beta, \max(\delta, \alpha P(t)))\Delta t, \tag{4}$$

for $t = 0, \ldots, N-1$ and $\alpha = \alpha_c \mathbb{1}_{\{P(t)>0\}} + \frac{1}{\alpha_d}\mathbb{1}_{\{P(t)<0\}}$. $B(0)$ is the initial state of the battery. If the battery is fully charged, $B(t) = B_{\max}$, it will only discharge if $P(t) < 0$. Otherwise if $P(t) > 0$ it remains at $B_{\max}$ and vice-versa for the empty state of the battery, i.e., when $B(t) = 0$.