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A cyclic time-dependent Markov process to model daily patterns in wind turbine power production

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ABSTRACT

Wind energy is becoming a top contributor to the renewable energy mix, which raises potential reliability issues for the grid due to the fluctuating nature of its source. To achieve adequate reserve commitment and to promote market participation, it is necessary to provide models that can capture daily patterns in wind power production. This paper presents a cyclic inhomogeneous Markov process, which is based on a three-dimensional state-space (wind power, speed and direction). Each time-dependent transition probability is expressed as a Bernstein polynomial. The model parameters are estimated by solving a constrained optimization problem: The objective function combines two maximum likelihood estimators, one to ensure that the Markov process long-term behavior reproduces the data accurately and another to capture daily fluctuations. A convex formulation for the overall optimization problem is presented and its applicability demonstrated through the analysis of a case-study. The proposed model is capable of reproducing the diurnal patterns of a three-year dataset collected from a wind turbine located in a mountainous region in Portugal. In addition, it is shown how to compute persistence statistics directly from the Markov process transition matrices. Based on the case-study, the power production persistence through the daily cycle is analyzed and discussed.

1. Introduction

The EC European Parliament objective to achieve 20% of the consumed energy from the renewable energy sector by 2020 introduced a serious challenge to the planning and operating of power systems. Wind energy is becoming a top contributor to the renewable energy mix due to rather high capacities and generation costs that are becoming competitive with conventional energy sources [28]. However, wind energy systems suffer from a major drawback, the fluctuating nature of their source, which affects the grid security, the power system operation and market economics. There are several tools to deal with these issues, such as the knowledge of wind power persistence and wind speed or power simulation. Persistence is related to stability properties and can provide useful information for bidding on the electricity market or to maintain reliability, e.g. by setting reserve capacity.

Wind power or speed simulation can be used to study the impact of wind generation on the power system. For this task, a sufficiently long time series of the power output from the wind plants should be used. However, real data records are commonly of short length and thus synthetic time series are generated by stochastic simulation techniques to model wind activity [16]. Shamshad et al. [23] used first and second-order Markov chain models for the generation of hourly wind speed time series. They found that a model with 12 wind speed states (1 m/s size) can capture the shape of the probability density function and preserve the properties of the observed time series. Additionally, they concluded that a second-order Markov chain produces better results. Nfaoui et al. [15] compared the limiting behavior of their Markov chain model with the data histograms gotten from hourly averaged wind speed and showed that the statistical characteristics were faithfully reproduced. Sahin and Sen [22] reported the use of a first-order Markov chain approach to simulate the wind speed, where: a) both transitions between consecutive times and within state wind speeds are sampled using a uniform distribution; and, b) extreme states are sampled with an exponential distribution. They showed that statistical parameters were preserved to a significant extent; however, second-order Markov chain models could yield improved results.

Although wind power can be computed from synthetic wind speed time series, Papaefthymiou and Klöckl [16] show that a stochastic model using wind power leads to a reduced number of states and a lower Markov chain model order. They compared a

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Nomenclature

α_0	initial state distribution at time step $t = 0$
$\beta_\mu^{i,j}$	coefficients of the Bernstein polynomial modeling the transition probability $p_{i,j}(t)$
$1_{\mathcal{A}}$	unit column vector of the same size as subset $\mathcal{A}$
$\mathbf{P}$	$P_0 \cdot \ldots \cdot P_{T-1}$
$\mathcal{A}$	subset of the state space, containing the states of interest for persistence
$\mathcal{S}$	set of observed state transitions
$\mathcal{S}_z$	set of transitions observed in the data together with the scaled time of the day z at which they are observed
ω	weight of the extra transitions added to the objective function
π	stationary distribution of a time-invariant Markov chain
π^*	$\lim_{t\to\infty} \mathbf{P}^t$
π_r	stationary distribution at time r of a time-variant cyclic Markov process
$\pi_r(j)$	stationary probability, of state j at time of the day r
$\pi_r(\mathcal{A})$	vector whose elements are the stationary probabilities of the states in the set $\mathcal{A}$ at time of the day r
τ	persistence
τ_r	time-dependent persistence in a cyclic Markov process
$b_{\mu,k}(z)$	μ-th Bernstein basis polynomial of order k
$E[]$	expected value operator
P_t	t-th step transition matrix of a Markov process
$p_{i,j}(t)$	t-th step transition probability of a Markov process
$p_{i,j}^{avg}$	daily average probability of transition from state s_i to s_j
r_t	remainder of time step t modulo T
S	Markov process state space
s_i	i-th state of a Markov process
T	period of a cyclic Markov process
t	time step of a Markov process
X_t	Markov process
z	scaled time of the day
$\pi_{\mathcal{A}}$	stationary probability distribution of the states in subset $\mathcal{A}$
r	time of the day

Markov chain based method for the direct generation of wind power time series with the transformed generated wind speed. Both the autocorrelation and the probability density function of the simulated data showed a good fit. Thus, they concluded that it is better to generate wind power time series. Chen et al. [7] also modeled wind power by using different discrete Markov chain models: the basic Markov model; the Bayesian Markov model, which considers the transition matrix uncertainty; and, the birth-and-death Markov model, which only allows state transitions between immediately adjacent states. After comparing the wind power autocorrelation function, the authors find the Bayesian Markov model best. Lopes et al. [13] proposed a Markov chain model using states that combine information about wind speed, direction and power. From the transition matrix, they compute statistics, such as the stationary power distribution and persistence of power production, which show a close agreement with their empirical analogs. The model was then used for the two-dimensional stochastic modeling of wind dynamics by Raischel et al. [21]. They aim at studying the interactions between wind velocity, turbine aerodynamics and controller action using a system of coupled stochastic equations describing the co-evolution of wind power and speed. They showed that both the deterministic and stochastic terms of the equations can be extracted directly from the Markov chain model.

The knowledge of wind power production persistence provides useful information to run a wind park and to bid on the electricity market, since it provides information about the expected power steadiness. It can be seen as the average time that a system remains in a given state or a subset of states. Existent literature focuses mainly on wind speed persistence, which is used for assessing the wind power potential of a region. Persistence can be determined directly from the data [20,19]; however, the presence of missing data leads to an underestimate of actual persistence. Alternative methods are based on wind speed duration curves [14,10], the autocorrelation function or conditional probabilities. Koçak [11] and Cancino-Solórzano et al. [5] compare these techniques, and both conclude that wind speed duration curve yields the best results, i.e. results that follow the geographical and climatic conditions of the analyzed sites. Moreover, Cancino-Solórzano et al. [5] analyze the concept of “useful persistence”, which is the time schedule series where the wind speed is between the turbine cut-in and cut-out speed. The results gotten from this analysis coincide with the persistence classification obtained using the speed duration curves. In addition, Koçak [12] suggests a detrended fluctuation analysis to detect long-term correlations and analyze the persistence properties of wind speed records. Sigl et al. [24]; Corotis et al. [8] and Poje [19] proposed an approach based on the use of a power law or exponential probability distributions for the persistence of wind speed above and below a reference value. A Markov chain based method to derive the distribution of persistence is introduced by Anastasiou and Tsekos [1], who show its capability on wind speed data.

Most methods in literature of wind speed and power synthesis fail to represent diurnal patterns in the artificial data. However, these are relevant for energy system modeling and design, since their knowledge allows to plan and schedule better. For instance, a power production behavior that best matches demand needs smaller reserve capacity. Recently, Suomalainen et al. [26,25] introduced a method for synthetic generation of wind speed scenarios that include daily wind patterns by sampling a probability distribution matrix based on five selected daily patterns and the mean speed of each day. Carapellucci and Giordano [6] adopt a physical–statistical approach to synthesize wind speed data and evaluate the influence of the diurnal wind speed profile on the cross-correlation between produced energy and electrical loads. The parameters of their model, such as diurnal pattern strength or peak hour of wind speed are determined through a multi-objective optimization, carried out using a genetic algorithm.

This paper introduces a cyclic time-variant Markov model of wind power, speed and direction designed to consider the daily patterns observed in the data. The model can be used to synthesize data for the three variables and is capable of reproducing the daily patterns. Moreover, it allows to compute persistence statistics depending on the time of the day. The paper is organized as follows: Section 2 introduces the proposed model as an extension of the “regular” Markov chain model, which is then used for comparison. Furthermore it is shown, how to compute the time of the day dependent persistence statistics directly from the Markov model transition matrices. In Section 3 the constrained convex optimization problem to get the model parameters is introduced and explained. It is applied to the analysis of a case-study based on a real dataset, Section 4. Since the model describes the joint