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A testing procedure for wind turbine generators based on the power grid statistical model

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ABSTRACT

In this study, a comprehensive test procedure is developed to test wind turbine generators with a hardware-in-loop setup. The procedure employs the statistical model of the power grid considering the restrictions of the test facility and system dynamics. Given the model in the latent space, the joint probability distribution of the scores is estimated and then transformed into the sample space. Knowing that the active power and the phase voltages are the applicable variables to the test bench, the conditional probability distribution of these variables is calculated considering the restrictions as prior information. Two approaches are proposed to generate testing data based on Gibbs sampler; off-line and on-line. In the off-line approach the data is generated for a time interval in advance while the on-line approach uses the current information to generate the next sample. The validation is performed using energy function method in which the testing data and the validation data are compared to evaluate the confidence level of following the same probability distribution.

1. Introduction

The worldwide concern about climate changes and global warming has led to increasing interest in technologies for generation of green and renewable electrical energy such as wind energy [1]. Wind energy has the potential to be the leading technology for providing the global energy demand by a truly sustainable and clean energy [2]. According to [3], with annual growth rate of 9.7%, there is now 141.6 GW of installed wind power capacity in the European Union. EWEA[1]'s new central scenario expects 192 GW of wind installations to produce 442 TWh meeting 14.9% of electricity consumption in 2020 [4].

Considering this rapidly increasing level of wind energy penetration, condition monitoring of turbines could provide a variety of economic and other benefits [5]. There are several condition monitoring methods for early detection and isolation of faults/failures so as to minimize downtime and maximize productivity [6–8]. Regarding existence of prior knowledge of the system dynamics, these methods can be categorized into data-driven or model-based. In the data-driven methods, the time series analysis is applied to the logged data to detect and identify the occurrence of a fault [9]. On the other hand, the model based methods employ state observers to estimate the system states and the concerned faults [10,11].

In a highly advanced test facility, wind turbines can be investigated prior to grid connection to evaluate their stability and reliability, especially during faults [12]. The investigation is performed by a hardware-in-the-loop (HIL) setup in anticipation of conditions experienced in real life. Given that the condition monitoring can also be applied prior to grid connection through HIL setup, the test facility can provide significant advantages in reducing cost and risk in the design and operation of wind turbine generators (WTGs) [13].

In the HIL test setup (so called test bench), the blades are disassembled and then the nacelle is connected to two hardwares; a prime mover (power source) and an electric load (power consumer). The prime mover is an electric motor which emulates the mechanical part of the WTG, i.e. wind kinetic energy and blades, and provides the mechanical force to rotate WTG's drive train. The electric load, e.g. a power converter, is a simulator of the power grid which consumes the produced electric power under a specified pattern. Given that some of the variables of these hardware simulators are controllable using control loops, for instance the mechanical power of the motor and the voltage of the converter, the

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Nomenclature

a	Optimum number of principal components
c	Confidence level
D	Distance function
$DPCA$	Dynamic principal component analysis
d	The euclidean distance between two samples
$\mathbf{E}$	Modeling error
F	Power grid frequency
f_S	Joint probability distribution function of scores
f_{S_i}	Probability distribution function of i^{th} score
f_{X^w}	Joint probability distribution of testing data
I_R, I_S, I_T	Three phase currents
l	The number of samples in a row of $\mathbf{X}$
m	Number of measured variables
n	Number of samples for each variable
n_w	Number of samples in a column of $\mathbf{X}$
P	Active power
Q	Reactive power
r	Dimension of X^{ξ}
$\mathbf{S}$	Score matrix of an arbitrary WTG
$\mathbf{S}_a$	Matrix of the first a scores of an arbitrary WTG
$\mathbf{S}^{\gamma}$	Score matrix of the generalized model
S_i^{γ}	The i^{th} column of $\mathbf{S}^{\gamma}$
$S_{X^{\alpha,\beta}}$	The transformed region spanned by (X^{α}, X^{β}) into the latent space
$\mathbf{X}$	Sample data matrix
$\widehat{\mathbf{X}}$	Validating data
$X(t)$	Sample data vector at time stamp t
$X^w(t)$	Row of $\mathbf{X}$ at time stamp t
$X^{\alpha}(t)$	The elements of $X(t)$ which can be applied to the test bench
$X^{\beta}(t)$	The elements of $X(t)$ dependent to $X^{\alpha}(t)$ and $X^{\delta}(t)$ and cannot be applied to the test bench
$X^{\delta}(t)$	The elements of $X(t)$ which are physically dictated by the test conditions
$X^{\delta}_{ref}(t)$	The reference value for $X^{\delta}(t)$
$X^{\iota}(t)$	The last state of the system
X^{ξ}	Data to be generated
$X^{\xi^{\nu}}$	Prior information to generate x_{ν}
x_{ν}	The sample generated in the ν^{th} iteration of the Gibbs Sampler
V_R, V_S, V_T	Three phase voltages
WTG	Wind turbine generator
w	Time lags in DCPA
Z_i	A random permutation of X and $\widehat{X}$
Δ_i	The energy of Z_i
$\Delta_{X\widehat{X}}$	The energy of the system having X and $\widehat{X}$
η	Weighting coefficient
Γ	Gamma function
$\mathbf{\Lambda}_a$	The first a λ_i s
λ_i	The i^{th} eigenvalue of $\mathbf{\Sigma}$
ν	Iteration number in the Gibbs Sampler
$\mathbf{\Sigma}$	Sample covariance matrix
$\mathbf{\Psi}$	Matrix of Principal components of an arbitrary WTG
$\mathbf{\Psi}_a$	Matrix of the first a principal components of an arbitrary WTG
$\mathbf{\Psi}^{\gamma}$	Matrix of principal components of the generalized model

task of a testing procedure is to determine the reference signals of these control loops.

The first step to study the interaction between WTGs and the power grid, is to model the power grid from wind farm stand point. Given this model, the goal of the test procedure is to generate Testing Data (reference signals) for WTGs which covers all possible conditions that may occur in a WTG's life-span. Grid codes and standards provide the basic testing procedures which use a simple model of the grid to evaluate the requirement for interconnection between WTGs and the power grid [14,15]. They also investigate some of the special conditions such as WTGs' fault-ride-through capability in the case of low and high voltage conditions.

The objective of this study is to propose a comprehensive test procedure of a WTG using a multivariate statistical model of the power grid. Compared to the grid codes, the contribution of this approach is to use a model which covers the diverse normal and faulty conditions that WTGs experience in reality. The model is presented by the authors of [16] in the latent space using dynamic principal component analysis (DPCA). They first derived the model of the power grid from one arbitrary WTG's standpoint [17] and then generalized it to a wind farm. The generalized model consists of two parts; principal components and scores which cover the variations of all WTGs in the wind farm. The generalized model, besides completeness, is computationally non-expensive to be used in the real time application of the test procedure. However since the model is statistical and in the latent space, several steps are necessary to generate Testing Data using this model.

In the statistical approach, the Testing Data is characterized by the joint probability distribution of its elements. To estimate this distribution, we fit an analytical function to the histogram of each score. The scores' distributions are mapped to the sample space to achieve the joint probability distribution of the Testing Data. A data sampling method is then required to generate random samples from the obtained joint probability distribution.

Drawing samples from a given distribution is straightforward in the case of having an unconditional Probability Density Function (PDF) [18]. However in the case of WTGs, there are some constraints which make the joint distribution conditional. The constraints are governed by the hardware of the test facility and the dynamics of the WTG. Given the conditional PDF, there are two approaches for sample-drawing; off-line and on-line. While the off-line approach provides the Testing Data for the whole period of testing in advance, the on-line approach generates the data at the time of testing only one step ahead based on the current state. For both approaches, we need to implement an algorithm to draw samples randomly given the conditional distribution. The implemented algorithm in this study is a customized version of Gibbs Sampling which is convenient in the case of drawing samples from a conditional distribution [18].

In order to investigate the validity of the whole process, Testing Data should be assessed by a new data set. Since we have used the logged data set of 2013 for modeling (Modeling Data), the logged data set of 2014 is employed for validation (Validation Data). Hence, the validation process in conducted by comparing the statistical properties of the Testing Data and the Validation Data. For such comparison, there are different suitable methods in univariate cases [19] and some of them are generalized to multivariate cases [20]. In this study the validation process is performed by utilizing the energy function which is a well-known method in multivariate cases [21].

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