Design optimization of offshore wind farms with multiple types of wind turbines

Most studies on offshore wind farm design assume a uniform wind farm, which consists of an identical type of wind turbines. In order to further reduce the cost of energy, we investigate the design of non-uniform offshore wind farms, i.e., wind farms with multiple types of wind turbines and hub-heights. Given a set of different types of wind turbines with a different default hub height for each type, we can specify the design of a wind farm by the types of turbines, number of turbines for each type, and turbine locations. We consider the optimization of such design to minimize the levelized cost of energy, which is calculated using a capital cost model that covers the turbine cost and the balance of plant cost. An empirical wind turbine design cost and scaling model is utilized to model the cost of turbines with different sizes.

Constraints on wind farm boundary, wind turbine proximity and total capacity are also included. We solve the problem with a newly developed extended random search algorithm and tested it in a realistic design optimization problem based on the Horns Rev 1 offshore wind farm in Denmark. The optimized non-uniform designs are compared with their uniform counterparts. We find that a non-uniform design can achieve a lower levelized cost of energy than its uniform counterparts, when the capital cost per MW is slightly lower for the smaller size turbine. Comparison with the mixed-discrete particle swarm optimization algorithm is also carried out for a non-uniform wind farm design problem with a fixed number of turbines, which shows the effectiveness and superiority of the proposed algorithm. Finally, the advantages and possible disadvantages of non-uniform design are also identified and discussed.
Wind farm power production in the changing wind: Robustness quantification and layout optimization

Wind farms operate often in the changing wind. The wind condition variations in a wide range of time scales lead to the variability of wind farms’ power production. This imposes a major challenge to the power system operators who are facing a higher and higher penetration level of wind power. Thus, wind farm developers/owners need to take the variability into consideration in the designing/planning stage, in addition to the conventional main objective of maximizing the expected power output under a fixed wind distribution. In this study, we first propose a new metric to evaluate the variability of wind power based on the characteristics of the wind farm and its local wind conditions. Then a series of robustness metrics are proposed to quantify wind farm’s ability to produce power with high mean value and low variability under changing wind, considering both short-term and long-term wind condition variations. Based on these metrics, wind farm layout optimization is performed to maximize the robustness of a real offshore wind farm in Denmark. The results demonstrate that the robustness metrics are more flexible and complete than the conventional metrics for characterizing wind farm power production, such as mean power output or wind power variability alone, and it is feasible to design wind farms to produce power with high mean value and low variability.
Multi-objective random search algorithm for simultaneously optimizing wind farm layout and number of turbines

A new algorithm for multi-objective wind farm layout optimization is presented. It formulates the wind turbine locations as continuous variables and is capable of optimizing the number of turbines and their locations in the wind farm simultaneously. Two objectives are considered. One is to maximize the total power production, which is calculated by considering the wake effects using the Jensen wake model combined with the local wind distribution. The other is to minimize the total electrical cable length. This length is assumed to be the total length of the minimal spanning tree that connects all turbines and is calculated by using Prim's algorithm. Constraints on wind farm boundary and wind turbine proximity are also considered. An ideal test case shows the proposed algorithm largely outperforms a famous multi-objective genetic algorithm (NSGA-II). In the real test case based on the Horn Rev 1 wind farm, the algorithm also obtains useful Pareto frontiers and provides a wide range of Pareto optimal layouts with different numbers of turbines for a real-life wind farm developer.

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Wind turbine wake measurement in complex terrain

SCADA data from a wind farm and high frequency time series measurements obtained with remote scanning systems have been analysed with focus on identification of wind turbine wake properties in complex terrain. The analysis indicates that within the flow regime characterized by medium to large downstream distances (more than 5 diameters) from the wake generating turbine, the wake changes according to local atmospheric conditions e.g. vertical wind speed. In very complex terrain the wake effects are often "overruled" by distortion effects due to the terrain complexity or topology.

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Reliable wind modelling is of crucial importance for wind farm development. The common practice of using sector-wise Weibull distributions has been found inappropriate for wind farm layout optimization. In this study, we propose a simple and easily implementable method to construct joint distributions of wind speed and wind direction, which is based on the parameters of sector-wise Weibull distributions and interpolations between direction sectors. It is applied to the wind measurement data at Horns Rev and three different joint distributions are obtained, which all fit the measurement data quite well in terms of the coefficient of determination R². Then, the best of these joint distributions is used in the layout optimization of the Horns Rev 1 wind farm and the choice of bin sizes for wind speed and wind direction is also investigated. It is found that the choice of bin size for wind direction is especially critical for layout optimization and the recommended choice of bin sizes for wind speed and wind direction is finally presented.
Solving the wind farm layout optimization problem using random search algorithm

Wind farm (WF) layout optimization is to find the optimal positions of wind turbines (WTs) inside a WF, so as to maximize and/or minimize a single objective or multiple objectives, while satisfying certain constraints. In this work, a random search (RS) algorithm based on continuous formulation is presented, which starts from an initial feasible layout and then improves the layout iteratively in the feasible solution space. It was first proposed in our previous study and improved in this study by adding some adaptive mechanisms. It can serve both as a refinement tool to improve an initial design by expert guesses or other optimization methods, and as an optimization tool to find the optimal layout of WF with a certain number of WTs. A new strategy to evaluate layouts is also used, which can largely save the computation cost. This method is first applied to a widely studied ideal test problem, in which better results than the genetic algorithm (GA) and the old version of the RS algorithm are obtained. Second it is applied to the Horns Rev 1 WF, and the optimized layouts obtain a higher power production than its original layout, both for the real scenario and for two constructed scenarios. In this application, it is also found that in order to get consistent and reliable optimization results, up to 360 or more sectors for wind direction have to be used. Finally, considering the inevitable inter-annual variations in the wind conditions, the robustness of the optimized layouts against wind condition changes is analyzed, and the optimized layouts consistently show better performance in power production than the original layout, despite of considerable variations in wind direction and speed. © 2015 Elsevier Ltd. All rights reserved.
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Scopus rating (2016): CiteScore 4.83 SJR 1.697 SNIP 2.044
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Web of Science (2014): Indexed yes
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Scopus rating (2013): SJR 2.066 SNIP 2.767 CiteScore 4.63
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ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
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Scopus rating (2011): SJR 1.688 SNIP 2.404 CiteScore 3.9
ISI indexed (2011): ISI indexed yes
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BFI (2010): BFI-level 1
Scopus rating (2010): SJR 1.494 SNIP 2.215
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Scopus rating (2007): SJR 1.214 SNIP 1.65
Web of Science (2007): Indexed yes
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Scopus rating (2005): SJR 1.215 SNIP 1.26
Scopus rating (2004): SJR 0.76 SNIP 1.154
Web of Science (2004): Indexed yes
Scopus rating (2003): SJR 0.965 SNIP 0.948
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Operating wind turbines in strong wind conditions by using feedforward-feedback control

Due to the increasing penetration of wind energy into power systems, it becomes critical to reduce the impact of wind energy on the stability and reliability of the overall power system. In precedent works, Shen and his co-workers developed a re-designed operation schema to run wind turbines in strong wind conditions based on optimization method and standard PI feedback control, which can prevent the typical shutdowns of wind turbines when reaching the cut-out wind speed. In this paper, a new control strategy combining the standard PI feedback control with feedforward controls using the optimization results is investigated for the operation of variable-speed pitch-regulated wind turbines in strong wind conditions. It is shown that the developed control strategy is capable of smoothening the power output of wind turbine and avoiding its sudden shutdown at high wind speeds without worsening the loads on rotor and blades.

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ISI indexed (2011): ISI indexed no
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.288 SNIP 0.344
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
Scopus rating (2009): SJR 0.253 SNIP 0.321
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 0.265 SNIP 0.294
Web of Science (2008): Indexed yes
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Web of Science (2007): Indexed yes
Wind farm layout optimization in complex terrain: A preliminary study on a Gaussian hill

One of the crucial problems for wind farm (WF) development is wind farm layout optimization. It seeks to find the optimal positions of wind turbines (WTs) inside a WF, so as to maximize and/or minimize a single objective or multiple objectives, while satisfying certain constraints. Although this problem for WFs in flat terrain or offshore has been investigated in many studies, it is still a challenging problem for WFs in complex terrain. In this preliminary study, the wind flow conditions of complex terrain without WTs are first obtained from computational fluid dynamics (CFD) simulation, then an adapted Jensen wake model is developed by considering the terrain features and taking the inflow conditions as input. Using this combined method, the wake effects of WF in complex terrain are properly modelled. Besides, a random search (RS) algorithm proposed in previous study is improved by adding some adaptive mechanisms and applied to solve the layout optimization problem of a WF on a Gaussian shape hill. The layout of the WF with a certain number of WTs is optimized to maximize the total power output, which obtained steady improvements over expert guess layouts.
Optimization of Wind Farm Layout: A Refinement Method by Random Search

Wind farm layout optimization is to find the optimal positions of wind turbines inside a wind farm, so as to maximize and/or minimize a single objective or multiple objectives, while satisfying certain constraints. Most of the works in the literature divide the wind farm into cells in which turbines can be placed, hence, simplifying the problem from with continuous variables to with discrete variables. In this paper, a refinement method, based on continuous formulation, by using random search is proposed to improve the optimization results based on discrete formulations. Two sets of optimization results of a widely studied test case are refined using the proposed method. One set of the results is from a published work using GA based on discrete formulation, the other set is the improved results using authors’ own GA code. Steady improvements are obtained for both sets of results.

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A minimax optimal control strategy for partially observable uncertain quasi-Hamiltonian systems

A stochastic minimax optimal control strategy for partially observable uncertain quasi-Hamiltonian systems is proposed. First, the stochastic optimal control problem of a partially observable nonlinear uncertain quasi-Hamiltonian system is converted into that of a completely observable linear uncertain system based on a theorem due to Charalambous and Elliot. Then, the converted stochastic optimal control problem is solved by a minimax optimal control strategy based on stochastic averaging method and stochastic differential game. The worst-case disturbances and the optimal controls are obtained by solving a Hamilton-Jacobi-Isaacs (HJI) equation. As an example, the stochastic minimax optimal control of a partially observable Duffing–van der Pol oscillator with uncertain disturbances is worked out in detail to illustrate the procedure and effectiveness of the proposed control strategy.

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BFI (2014): BFI-level 2
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Web of Science (2014): Indexed yes
BFI (2013): BFI-level 2
Scopus rating (2013): SJR 0.917 SNIP 1.47 CiteScore 1.81
ISI indexed (2013): ISI indexed yes
BFI (2012): BFI-level 2
Scopus rating (2012): SJR 0.693 SNIP 1.454 CiteScore 1.41
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
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Scopus rating (2011): SJR 0.807 SNIP 1.592 CiteScore 1.64
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BFI (2010): BFI-level 2
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Web of Science (2007): Indexed yes
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Scopus rating (2005): SJR 1.719 SNIP 1.722
Scopus rating (2004): SJR 1.312 SNIP 1.574
Scopus rating (2003): SJR 0.994 SNIP 1.32
A minimax stochastic optimal semi-active control strategy for uncertain quasi-integrable Hamiltonian systems using magneto-rheological dampers

A minimax stochastic optimal semi-active control strategy for stochastically excited quasi-integrable Hamiltonian systems with parametric uncertainty by using magneto-rheological (MR) dampers is proposed. Firstly, the control problem is formulated as an n-degree-of-freedom (DOF) controlled, uncertain quasi-integrable Hamiltonian system and the control forces produced by MR dampers are split into the passive part and the semi-active part. Then the passive part is incorporated into the uncontrolled system. After that, the stochastic optimal semi-active control problem is solved by applying the minimax stochastic optimal control strategy based on the stochastic averaging method and stochastic differential game. The worst-case disturbances and the optimal controls are obtained by the minimax dynamical programming equation with the constraints of disturbance bounds and MR damper dynamics. Finally, the system response and the control performance are evaluated by using Monte Carlo simulation. An example of a two-DOF system with coupling damping and parametric uncertainty under Gaussian white noise excitations is worked out in detail to illustrate the procedure and effectiveness of the proposed control strategy, which is also compared with the clipped linear-quadratic-Gaussian control strategy to show the advantages.
Control of variable speed pitch-regulated wind turbines in strong wind conditions using a combined feedforward and feedback technique

Due to the increasing penetration of wind energy into power systems, it becomes critical to reduce the impact of wind energy on the stability and reliability of the overall power system. In precedent works, Shen and his co-workers developed a re-designed operation schema to run wind turbines in strong wind conditions based on optimization method and standard PI feedback control, which can prevent the typical shutdowns of wind turbines when reaching the cut-out wind speed. In this paper, a new control strategy combing the standard PI feedback control with feedforward controls using the optimization results is investigated for the operation of variable-speed pitch-regulated wind turbines in strong wind conditions. It is shown that the developed control strategy is capable of smoothening the power output of wind turbine and avoiding its sudden showdown at high wind speeds without worsening the loads on rotor and blades.

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The robustness of feedback stabilization for quasi non-integrable Hamiltonian systems with uncertain parameters is investigated. The uncertain parameters are modeled as bounded random variables with $\lambda$-probability density function. Based on the independence of uncertain parameters and stochastic excitations, a feedback control to asymptotically stabilize, with probability one, the nominal system (with average parameter values) is firstly obtained by applying the stochastic averaging method, the expression for the Lyapunov exponent of quasi non-integrable Hamiltonian systems and the stochastic dynamical programming principle. Then, the mean and standard deviations of the Lyapunov exponent of the uncertain quasi non-integrable Hamiltonian system are calculated by using the stochastic averaging method and probabilistic analysis. Finally, the robustness of the feedback stabilization for quasi non-integrable Hamiltonian systems with parametric uncertainty is evaluated in terms of the sensitivity of the variation coefficient of the Lyapunov exponent of a controlled system to the variation coefficients of uncertain parameters. An example is worked out to illustrate the robustness of the feedback stabilization.
**Stochastic optimal control analysis of a piezoelectric shell subjected to stochastic boundary perturbations**

The stochastic optimal control for a piezoelectric spherically symmetric shell subjected to stochastic boundary perturbations is constructed, analyzed and evaluated. The stochastic optimal control problem on the boundary stress output reduction of the piezoelectric shell subjected to stochastic boundary displacement perturbations is presented. The electric potential integral as a function of displacement is obtained to convert the differential equations for the piezoelectric shell with electrical and mechanical coupling into the equation only for displacement. The displacement transformation is constructed to convert the stochastic boundary conditions into homogeneous ones, and the transformed displacement is expanded in space to convert further the partial differential equation for displacement into ordinary differential equations by using the Galerkin method. Then the stochastic optimal control problem of the piezoelectric shell in partial differential equations is transformed into that of the multi-degree-of-freedom system. The optimal control law for electric potential is determined according to the stochastic dynamical programming principle. The frequency-response function matrix, power spectral density matrix and correlation function matrix of the controlled system response are derived based on the theory of random vibration. The expressions of mean-square stress, displacement and electric potential of the controlled piezoelectric shell are finally obtained to evaluate the control effectiveness. Numerical results are given to illustrate the high relative reduction in the root-mean-square boundary stress of the piezoelectric shell subjected to stochastic boundary displacement perturbations by the optimal electric potential control.

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Web of Science (2015): Indexed yes
BFI (2014): BFI-level 1
Electric potential response analysis of a piezoelectric shell under random micro-vibration excitations

The response characteristics of a spherically symmetric piezoelectric shell under random boundary micro-vibration excitations are analyzed and calculated. The equation for electric potential is integrated radially to obtain the electric potential as a function of displacement, so that the differential equations for the piezoelectric shell with electrical and mechanical coupling are converted into an equation only for the displacement. The displacement transformation is constructed to convert the random boundary conditions into homogeneous ones, and the transformed displacement is expanded in space to further convert the partial differential equation for the displacement into ordinary differential equations using the Galerkin method. The equations represent a multi-degree-of-freedom dynamic system with an asymmetric stiffness matrix under random micro-vibration excitations. The frequency-response function matrix, power spectral density matrix and correlation function matrix of the system response are derived from these equations based on the theory of random vibration. The expressions of mean-square displacement, stress and electric potential of the piezoelectric shell are finally obtained and illustrated by numerical results for random micro-vibration excitations. The random electrical and mechanical coupling properties, in particular the relations between boundary electric potential responses and micro-displacement excitations, are explored.

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Stochastic micro-vibration response of a spherically symmetric piezoelectric shell structure as sensor

The micro-vibration monitoring and control of vibration-sensitive precision facilities are important and the accurate measurement of micro-vibrations is necessary. The piezoelectric sensors such as piezoelectric shell structure have better electrical-mechanical coupling properties and less effect of bulk and weight. This paper studies the response characteristics of an interceptive spherical piezoelectric shell under stochastic boundary micro-vibration excitations. The equation for electric potential is integrated, and the displacement is transformed and expanded to yield the ordinary differential equations for the shell. The frequency-response function, power spectral density and correlation function matrices of the shell system response are derived. Then the root-mean-square displacement, stress and electric potential of the piezoelectric shell can be calculated. The numerical results are given to illustrate the stochastic electrical-mechanical coupling properties and the relation between boundary electric potential responses and micro-vibration excitations.
Stochastic minimax optimal time-delay state feedback control of uncertain quasi-integrable Hamiltonian systems

A stochastic minimax optimal time-delay state feedback control strategy for uncertain quasi-integrable Hamiltonian systems is proposed. First, a stochastic optimal state feedback control problem of uncertain quasi-integrable Hamiltonian system with time delay in feedback control subjected to Gaussian white noise is formulated. Then, the time-delayed state feedback control forces are approximated by the control forces without time delay and the original problem is converted into a stochastic optimal state feedback control problem of an uncertain system without time delay. After that, by following a procedure based on the stochastic averaging method and stochastic differential game, the worst-case disturbances and the optimal controls are obtained from solving a Hamiltonian–Jacobi–Isaacs (HJI) equation. As an example, the stochastic minimax optimal state feedback control of a Duffing oscillator with parametric disturbances and time-delayed feedback control is worked out in detail to illustrate the procedure and effectiveness of the proposed control strategy.
A nonlinear stochastic optimal time-delay control strategy for quasi-integrable Hamiltonian systems is proposed. First, a stochastic optimal control problem of quasi-integrable Hamiltonian system with time-delay in feedback control subjected to Gaussian white noise is formulated. Then, the time-delayed feedback control forces are approximated by the control forces without time-delay and the original problem is converted into a stochastic optimal control problem without time-delay. After that, the converted stochastic optimal control problem is solved by applying the stochastic averaging method and the stochastic dynamical programming principle. As an example, the stochastic time-delay optimal control of two coupled van der Pol oscillators under stochastic excitation is worked out in detail to illustrate the procedure and effectiveness of the proposed control strategy.
Projects:

Wind Farm Layout Optimization in Complex Terrain
The overall objective of the project is to develop and provide new reliable tools for designing wind farms located in complex terrain through full scale measurements in wind farms. For wind farms located in flat terrain, the performance of the wind turbines is significantly influenced by the upstream wind turbines and slightly influenced by the ground. For wind farms located in complex terrain the ground effects are relatively more pronounced, as such effects may bend the wakes created by the upstream turbines significantly. The goal of the present Sino-Danish project is to further develop Danish wind farm technology by using measured wind farm data from complex terrain wind farms in China, which is convenient, as Denmark does not have complex terrain that can be used for developing/validating such technology. To improve the wind turbines’ performance within wind farms in complex terrain, there are basically three important steps: (1) develop reliable CFD tools for predicting flow in complex terrain with and without wind turbines; (2) develop simplified flow models for predicting wind turbine performance in complex terrain; and (3) design high efficiency wind turbine parks in complex terrain.

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Project Manager, academic:
Zhu, Wei Jun (Intern)
Hansen, Kurt Schaldemose (Intern)
Bechmann, Andreas (Intern)
Larsen, Gunner Chr. (Intern)
Feng, Ju (Intern)
Project Coordinator:
Shen, Wen Zhong (Intern)

Relations
Activities:
Wind farm design in complex terrain - the FarmOpt methodology

Activities:

Wind farm design in complex terrain - the FarmOpt methodology
Period: 18 Oct 2017
Ju Feng (Invited speaker)
Wen Zhong Shen (Other)

Department of Wind Energy
Fluid Mechanics

Description
Invited speaker at the conference on 18th October in the session "Wind Farm Micro Siting".
Degree of recognition: International

Documents:
Wind farm design in complex terrain - the FarmOpt methodology _Ju Feng _DTU (2017)

Related event
China Wind Power 2017
17/10/2017 → 19/10/2017
Beijing, China
Activity: Talks and presentations › Conference presentations