Editorial
To Tame the Wind: Advanced Control Applications in Wind Energy

WITH AN average yearly growth of almost 30% of the installed capacity in the last years and a global investment for new installations of more than $67 billion in 2009, corresponding to about 60% of the 2009 global investment in renewables and to an increase of 14% over 2008, despite the financial crisis, wind power is the world's fastest growing renewable energy technology. Electricity generation from wind power is projected to reach 4.5% of total electricity generation in 2030 worldwide. In the OECD countries, this share is expected to reach 8% in 2030. Wind power is projected to soon become the most significant source of renewable-based electricity after hydropower, ahead of biomass. Indeed, estimates based on measured data indicate that global wind power alone could supply the entire world's energy demand.

Yet, the share of global electricity generated from wind power is actually only about 1% worldwide and about 2% in OECD countries. In addition, the current growth rate of global wind power installations, and of renewable energy plants in general, is still not sufficient to meet the ambitious objectives that most major countries have adopted, like the European Union's 20-20-20, which aims at supplying 20% of the total European primary energy consumption with renewable energies by the year 2020.

The main reasons that prevent the development of wind power plants, in spite of the significant potential of this energy source, are the high cost of the technology per unit of energy produced, the variability of the resource, and the low density of generated power per unit area. With the aim of tackling these issues, significant research and development activities are undergoing worldwide and will be more and more intensive in the future, thanks to the consistent programs planned or adopted by most major countries, like the € 6 billion European industrial initiative on wind energy.

In this context, the role of control engineering is crucial to achieve the required improvements in wind technology. Advanced control strategies are needed to maximize the efficiency of wind turbines while limiting vibrations and yaw and tilt moments, thus allowing for lighter structures and larger turbines. Reliable wind and turbine models are of paramount importance for design and operation of wind power plants; research efforts are being made to obtain better models both for single turbines and for the interactions between the towers operating in a wind farm. As for the latter aspect, co-ordinated control strategies can help improving the overall performance of wind farms by coping with wake effects. Research studies are also ongoing, regarding the effects of the increasing penetration of wind power sources in the power grid, to assess the real potential of wind power plants to supply significant shares of the energy demand and to devise optimal and robust grid control strategies, able to minimize energy losses in front of the variability of both the wind energy source and the energy demand. In the field of control for offshore wind turbines, research efforts are aimed to grid integration and to structural control of floating wind turbines, to improve their reliability and reduce the operations and maintenance costs. Finally, airborne wind energy technologies are being developed by several research groups and companies worldwide, with the goal to reach high-altitude winds. In these novel concepts of wind generators, control engineering plays an essential role.

The aim of this special section is to illustrate the potential of advanced control methods to improve wind power technologies, through a collection of contributions concerned with several aspects including mitigation of tower vibration and fatigue loads, wind preview control, estimation of rotor effective wind speed, identification of rotor dynamics, fault tolerant control, wind farm control, and airborne wind energy.

A significant number of contributions in the section are concerned with mitigation of vibrations and load reduction of wind turbines, in different frameworks and with different actuators and control approaches. The paper "Tower Vibration Control of Active Stall Wind Turbines," by C. J. Spruce and J. K. Turner, describes a control approach to avoid the amplification of tower vibrations on turbines with stall rotors. The effectiveness of the solution is shown by measured data from thousands of V82-1.65 MW turbines, and the control software is now in operation on more than 5 GW of installed wind turbines. Assessing the achieved load reduction in experimental tests is the aim of the paper "Validation of Individual Pitch Control by Field Tests on Two- and Three-Bladed Wind Turbines," by E. Bossanyi, P. Fleming, and A. Wright. The reported experimental results demonstrate convincingly that the load reductions predicted by simulation tools can be achieved in practice. S. Schuler, D. Schlipf, P. W. Cheng, and F. Allgöwer, in their paper "ℓ_1-Optimal Control of Large Wind Turbines," employ individual pitch control to decrease the blade root bending moment, and present an ℓ_1-control setup for collective pitch control. Simulations with a full nonlinear aeroelastic model show the applicability of the control strategy and the achieved significant load reduction. The paper "LPV Identification of Wind Turbine Rotor Vibrational

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Dynamics Using Periodic Disturbance Basis Functions," by P. M. O. Gebraad, J.-W. van Wingerden, P. A. Fleming, and A. D. Wright, is concerned with the problem of identification of the coupled dynamics of the edgewise bending vibrations of the rotor blades and the in-plane motion of the drivetrain. The paper demonstrates that these phenomena can be captured in a linear parameter-varying model, which is identified from measured data. The paper "Offshore Wind Turbine Load Reduction Employing Optimal Passive Tuned Mass Damping Systems" by G. Stewart and M. Lackner, develops optimum passive tuned mass dampers for different types of offshore structures. The simulation results presented by the authors indicate tower fatigue damage reductions of up to 20% for the various configurations. The manuscript "Frequency-Weighted Model Predictive Control of Trailing Edge Flaps on a Wind Turbine Blade," by D. Castaignet, I. Couchman, N. K. Poulsen, T. Buhl, and J. J. Wedel-Heinen, presents the load reduction achieved with trailing edges flaps during a full-scale test on a Vestas V27 wind turbine. A frequency-weighted linear model predictive control (MPC) approach is implemented by the authors, and an average of 13.8% flapwise blade root fatigue load reduction is measured.

MPC is applied also in the paper "Combined Feedback-Feedforward Control of Wind Turbines Using State-Constrained Model Predictive Control" by A. Koerber and R. King, where the wind turbine collective pitch and torque control problem in full load operation is considered. Preview control and state constraints in the MPC are found to provide significant benefits in different scenarios.

The use of wind preview measurements is considered also in the next three papers. N. Wang, K. E. Johnson, and A. D. Wright, in their paper "Comparison of Strategies for Enhancing Energy Capture and Reducing Loads using LIDAR and Feedforward Control," compare the baseline $k\Omega^2$ control scheme and three advanced LIDAR-enabled torque controllers through simulations with measured turbulent wind data. The results show that LIDAR-enabled controllers have only a small effect on energy capture, but they bring forth advantages when a combination of fatigue load mitigation and power capture is considered. In the paper "Design Tradeoffs of Wind Turbine Preview Control" by A. A. Ozdemir, P. Seiler, and G. J. Balas, interesting insights into the fundamental performance limits of preview control are derived, as a function of preview time, wind turbulence intensity, and blade pitch actuator speed, which are then confirmed by simulations on a nonlinear turbine model. M. Kristalny, D. Madjidian, and T. Knudsen, in their paper "On Using Wind Speed Preview to Reduce Wind Turbine Tower Oscillations," show how the problem of using wind preview to reduce tower loads can be formulated as an H_2 model matching optimization with preview, which can be solved to design the controller. The approach facilitates the analysis of the effects of measurement distortion and the required preview length.

The problem of tracking the maximum delivered power for variable speed wind turbines is considered in the paper "Robust Control of Variable-Speed Wind Turbines based on an Aerodynamic Torque Observer" by M. L. Corradini, G. Ippoliti, and G. Orlando, using sliding mode techniques to design a controller capable of tracking robustly the maximum power coefficient, in the presence of model uncertainty and disturbances.

The paper "Estimation of Rotor Effective Wind Speed: A Comparison" by M. Soltani, T. Knudsen, M. Svenstrup, R. Wisniewski, P. Brath, R. Ortega, and K. Johnson, provides a comparison, on both aero-servo-elastic turbine simulations and real turbine field experiments, of different algorithms aimed to estimate the rotor effective wind speed using common turbine measurements.

The paper "Fault Tolerant Control of Wind Turbines: A Benchmark Model" by P. F. Odgaard, J. Stoustrup, and M. Kinnaert, presents a test benchmark model for the evaluation of fault detection and accommodation schemes at system level. The FDI problem was addressed by several teams, and five of the proposed solutions are compared in the second part of the manuscript.

J. R. Marden, S. D. Ruben, and L. Y. Pao study the problem of wind farm control in their paper "A Model-Free Approach to Wind Farm Control Using Game Theoretic Methods." By exploiting recent results in game theory and co-operative control, the authors aim to devise an optimal control strategy for the wind farm without explicitly modeling the aerodynamic interaction amongst the turbines.

Finally, a study in the field of airborne wind energy is described in the manuscript "Airborne Wind Energy Based on Dual Airfoils," by M. Zanon, S. Gros, J. Andersson, and M. Diehl. The use of two wings with a shared tether is studied by means of numerical optimization and compared with single-airfoil systems at small, medium, and large scales.

In summary, the authors contributed a great collection of papers, which highlighted the role and the potential of control engineering in wind energy. We were happy to provide the readership of the IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY with this special section.

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Dr. Rotea is a fellow of the IEEE for contributions to robust and optimal control of multivariable systems.

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