NATIONAL RENEWABLE ENERGY LABORATORY



Grid Integration Science

NREL Power Systems Engineering Center

2015 Publications Summary

The National Renewable Energy Laboratory's (NREL's) Power Systems Engineering Center published 33 journal and magazine articles in the past year highlighting recent research in integrating renewable energy into power systems. For information about these or any other NREL articles or reports, please contact me or the author(s). NREL acknowledges the U.S. Department of Energy for the funding support that made this research possible.

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Integrated Devices and Systems Research

Lab Tests: Verifying That Smart Grid Power Converters Are Truly Smart, *IEEE Power and Energy Magazine*

This article describes the advanced functions and control modes currently being implemented in distributed energy resource (DER) power converters. It presents the facilities and features of new test labs that have recently been built in Europe as well as the United States to facilitate the testing and certification of new DERs with advanced grid support functions. Case studies from three different labs highlight the testing methods and principles applied to validate key functionalities.

Power Hardware-in-the-Loop Platform With Remote Distribution Circuit Cosimulation, *IEEE Transactions on Industrial Electronics*

This paper demonstrates a novel cosimulation architecture that integrates hardware testing using power-hardware-in-the-loop (PHIL) techniques with larger-scale electric grid models using off-the-shelf, non-PHIL software tools. This test bed for distributed integration enables utilities to study the impacts of emerging energy technologies on their systems and manufacturers to explore the interactions of new devices with existing and emerging devices on the electric power system, both without the need to convert existing grid models to a new platform or to conduct in-field trials.

Gearbox and Drivetrain Models to Study Dynamic Effects of Modern Wind Turbines, *IEEE Transactions on Industry Applications*

In this work, the capability of the Fatigue, Aerodynamics, Structures, and Turbulence (FAST) wind turbine computer-aided engineering tool, developed by NREL, is enhanced through the integration of a dynamic model of the drivetrain. The dynamic drivetrain model is built using Simscape in the MATLAB/Simulink environment and incorporates detailed electrical generator models. This model can be used in the future to test advanced control schemes to extend the life of the gearbox.

Modeling and Control of Type-2 Wind Turbines for Sub-Synchronous Resonance Damping, *Energy Conversion and Management*

This paper demonstrates that Type 2 wind turbine generators (WTGs) might induce sub-synchronous resonance (SSR) events when connected to a series-compensated transmission line, and with proper control, they might also suppress such events. The paper presents a complete dynamic model tailored to study via eigenanalysis SSR events in the presence of Type 2 WTGs and a systematic procedure to design a power system stabilizer using only local and measurable signals. Results are validated through a case study based on the IEEE first benchmark model for SSR studies as well as with transient computer simulations.

Power Quality Surveys of Photovoltaic Power Plants: Characterisation and Analysis of Grid-Code Requirements, *IET Renewable Power Generation*

This study analyzes intensive power quality surveys carried out from 2008 to 2011 in three photovoltaic (PV) power plants in Spain: a fixed-array installation with 4 MW of PV power capacity, a PV power plant including dual-axis trackers with 1 MW of PV power capacity, and a fixed-array PV power plant with 5 MW of PV power capacity. The paper discusses several methods to characterize the monitored disturbances and compares these events to current grid code requirements. Further, the time interval around the residual voltage is proposed and defined by the authors as an additional parameter to provide a complete characterization of the severity of the disturbances. Results from the characterizations of collected data and comparisons to current requirements are included.

Interarea Oscillation Damping Controls for Wind Power Plants, *IEEE Transactions on Sustainable Energy*

This paper investigates the potential for wind power plants (WPPs) to damp interarea modes. Interarea modes might be the result of a single or a group of generators oscillating against another group of generators across a weak transmission link. If poorly damped, these power system oscillations can cause system instability and potentially lead to blackouts. Power conversion devices, particularly megawatt-scale converters that connect wind turbines and photovoltaic power plants to the grid, could be used to damp these oscillations by injecting power into the system out of phase with the potentially unstable mode. In this model, the power might be provided by a WPP. This is a measurement-based investigation that employs simulated measurement data. Analysis is performed on the data generated by the simulations.

Review of Marine Hydrokinetic Power Generation and Power Plant, *Electric Power Components and Systems*

This article covers the broad spectrum of marine hydrokinetic generation. Marine hydrokinetic power generation is a relatively new type of renewable generation. Its predecessors—including wind power generation, hydropower plant generation, geothermal generation, photovoltaic generation, and solar thermal generation—have gained attention because of their successful implementations. The successful integration of renewable generation into the electric power grid has energized the power system global communities to take the lessons learned, innovations, and market structure to focus on the large potential of marine hydrokinetic power generation to contribute to the pool of renewable energy generation. The state of the art of power take-off is discussed. Types of electrical generators are presented, and the options for implementation are also presented.

Guest Editorial: Optimal Design of Electric Machines, *IEEE Transactions on Energy Conversion*

The papers in this special edition cover the advances in multi-objective design and optimization based on genetic algorithms, surrogate, polynomial regression, and particle swarm optimization techniques. The design of novel trans-rotary magnetic gear, hybrid machines for DC generation, and two-degrees-of-freedom split-stator induction machines highlight new magnetic configurations and their performance evaluations. Multiphysics analysis of magnetothermal and magnetostructural behavior of switched reluctance motor and brushless doubly-fed machines shed light on analytical and practical aspects of design in electromechanical converters. Finally, control of torque undulation; loss minimization; low-speed, high-torque operation; and advanced digital control of adjustable-speed motor drives conclude this unique collection.

Energy Storage in the Future Grid, *IEEE Electrification Magazine*

This paper discusses energy storage options for the electric grid in the future. The future grid will contain increasing amounts of variable generation from wind and solar energy. These sources produce power based on the availability of the solar and wind resources. Integrating these technologies at a significant scale will require a much more flexible grid that can respond quickly to this variability and uncertainty of the generation source. This will require a new operational paradigm where storage plays an increasing role and loads are responsive and follow available generation. Energy storage can improve the operating capabilities of the grid and address issues with the timing, transmission, and dispatch of electricity. It can also regulate the quality and reliability of power generated by traditional and variable sources.

Energy Storage, Renewable Power Generation, and the Grid: NREL Capabilities Help to Develop and Test Energy-Storage Technologies, *IEEE Electrification Magazine*

The continued growth of renewable power generation could lead to a sustainable energy future with lower greenhouse gas emissions. A recent trend highlighting this growth is the installation of solar and wind power generation exceeding that of new conventional power generation from coal and nuclear power plants. Further, the cost of electricity generation by solar and wind is rapidly approaching grid parity in many regions of the world. This paper explores these trends.

Power System Design and Planning Research

An Energy Signal Tool for Decision Support in Building Energy Systems, *Applied Energy*

This paper demonstrates a prototype energy signal tool for operational whole-building and system-level energy use evaluation. The purpose of the tool is to give a summary of building energy use that allows a building operator to quickly distinguish normal and abnormal energy use. The expected energy use is represented by a probability distribution. Energy use is modeled by a low-order lumped parameter model. Uncertainty in energy use is quantified by a Monte Carlo exploration of the influence of model parameters on energy use. Distributions over model parameters are updated over time via Bayes' theorem. The simulation study is devised to assess whole-building energy signal accuracy in the presence of uncertainty and faults at the submetered level, which might lead to trade-offs at the whole-building level not detectable without submetering.

In Divergence There Is Strength: Measuring and Mitigating Solar PV Impacts in Southern California Using Power Factors Other Than One, *IEEE Power and Energy Magazine*

Distribution-system, interconnected, utility-scale photovoltaic (PV) systems (500 kW–5 MW) have become commonplace in many utilities' service areas since the first few systems were installed in the 2010–2011 time frame. Integrating these systems within the operating framework of the traditional utility distribution system creates many challenges. The goal of these integration efforts is to ensure the safe, reliable, and cost-effective operation of the resulting distribution system—but with the added benefit of a considerable amount of PV-based distributed generation, resulting in lower carbon emissions and compliance with state energy policies and standards.

Designing Electricity Markets for a High Penetration of Variable Renewables, *Wiley Interdisciplinary Reviews: Energy and Environment*

Renewable technologies are often characterized as being somewhat different from conventional generating technologies in three ways: (1) some have highly variable and somewhat uncertain availability, meaning that electricity markets must be designed to elicit adequate flexibility; (2) many have very low short-run marginal costs (operating costs), meaning that the mechanisms for managing resource adequacy must be carefully considered; and (3) some are nonsynchronous, meaning that grid codes and regulatory requirements must be appropriately designed. This paper explores the design of markets for frequency control ancillary services (FCAS), which provide opportunities to increase access to flexibility by creating active real-time markets for a wide range of FCAS, allowing renewable technologies to provide FCAS, and determining FCAS reserve requirements dynamically in real time.

Power System Operations and Controls Research

Guest Editorial: Advanced Distributed Control of Energy Conversion Devices and Systems, *IEEE Transactions on Energy Conversion*

The papers in this special issue on advanced distributed control of energy conversion devices and systems are loosely grouped into three categories: (1) AC energy conversion systems, (2) DC energy conversion systems, and (3) optimization and standards.

Decentralized Optimal Dispatch of Photovoltaic Inverters in Residential Distribution Systems, *IEEE Transactions on Energy Conversion*

Decentralized methods for computing optimal real and reactive power set points for residential photovoltaic (PV) inverters are developed in this paper. It is known that conventional PV inverter controllers, which are designed to extract maximum power at unity power factor, cannot address secondary performance objectives such as voltage regulation and network loss minimization. Optimal power flow techniques can be utilized to select which inverters will provide ancillary services and to compute their optimal real and reactive power set points according to well-defined performance criteria and economic objectives. Leveraging advances in sparsity-promoting regularization techniques and semidefinite relaxation, this paper shows how such problems can be solved with reduced computational burden and optimality guarantees..

Optimal Dispatch of Residential Photovoltaic Inverters Under Forecasting Uncertainties, *IEEE Journal of Photovoltaics*

This paper discusses ancillary service procurement in the face of solar irradiance forecasting errors. In particular, assuming that forecasted photovoltaic (PV) irradiance can be described by a random variable with known (empirical) distribution, the proposed uncertainty-aware optimal inverter dispatch framework indicates which inverters should provide ancillary services with a guaranteed a priori risk level of PV generation surplus. To capture forecasting errors and strike a balance between the risk of overvoltages and (re) active power reserves, the concept of conditional value at risk is advocated.

Photovoltaic Inverter Controller Seeking AC Optimal Power Flow Solutions, *IEEE Transactions on Power Systems*

This paper considers future distribution networks featuring inverter-interfaced photovoltaic (PV) systems, and it addresses the synthesis of feedback controllers that seek real and reactive power inverter set points corresponding to AC optimal power flow (OPF) solutions. The objective is to bridge the temporal gap between long-term system optimization and real-time inverter control and enable seamless PV-owner participation without compromising system efficiency and stability. The design of the controllers is grounded on a dual epsilon-subgradient method, and semidefinite programming relaxations are advocated to bypass the nonconvexity of AC OPF formulations. Global convergence of inverter output powers is analytically established to diminish step-size rules and strictly convex OPF costs for cases where: (1) computational limits dictate asynchronous updates of the controller signals, and (2) inverter reference inputs might be updated at a faster rate than the power-output settling time. Although the focus is on PV systems, the framework naturally accommodates different types of inverter-interfaced energy resources.

Demand Response Exchange in the Stochastic Day-Ahead Scheduling With Variable Renewable Generation, *IEEE Transactions on Sustainable Energy*

This paper proposes a pool-based demand response exchange (DRX) model in which economic demand response is traded among demand-response participants as an alternative for managing the variability of renewable energy sources. Load curtailment bids are provided by individual DRX participants, and the DRX is cleared by maximizing the total social welfare, which is subject to supply-demand balance and individual bidders' inter-temporal operation constraints. The proposed DRX model is further integrated in the current context of the independent system operator's (ISO's) day-ahead scheduling in electricity markets. Numerical tests are performed for a 6-bus system and an IEEE 118-bus system. The results demonstrate the benefit of utilizing the DRX model for customer market participation in the ISO's day-ahead market scheduling.

Integrating Solar PV (Photovoltaics) in Utility System Operations: Analytical Framework and Arizona Case Study, *Energy*

This paper proposes a systematic framework to estimate the impact on operating costs due to uncertainty and variability in renewable resources. The framework quantifies the integration costs associated with subhourly variability and uncertainty as well as day-ahead forecasting errors in solar photovoltaics power. A case study illustrates how changes in system operations might affect these costs for a utility in the southwestern United States (Arizona Public Service Company). The authors conduct an extensive sensitivity analysis under different assumptions about balancing reserves, system flexibility, fuel prices, and forecasting errors.

Guest Editorial Introduction to the Special Issue on "Advanced Signal Processing Techniques and Telecommunications Network Infrastructures for Smart Grid Analysis, Monitoring, and Management, *EURASIP Journal on Advances in Signal Processing*

This paper addresses the problems inherent to the study of advanced signal processing techniques and telecommunications network infrastructures that are needed for modern smart grids. The evolution of power distribution networks involves an increasingly complex information and communication technology infrastructure. An increasing and continuous flow of information will be exchanged among the various levels of such systems to ensure the optimized operation of the network and the efficient management of distributed resources. In addition, smart grids operate with two-way flows of electricity and information. The necessary communication resources heavily depend on the choices related to the required signal processing for the analysis, monitoring, and management of the network. This special issue explores and addresses these issues.

Investigating the Impacts of Wind Generation Participation in Interconnection Frequency Response,
EEEE Transactions on Sustainable Energy

The electrical frequency of an interconnection must be maintained very close to its nominal level at all times. Excessive frequency deviations can lead to load shedding, instability, machine damage, and even blackouts. There is rising concern in the power industry in recent years about the declining amount of inertia and primary frequency response (PFR) in many interconnections. This decline might continue because of increasing penetrations of inverter-coupled generation and the planned retirements of conventional thermal plants. Inverter-coupled variable wind generation is capable of contributing to PFR and inertia; however, wind generation PFR and inertia responses differ from those of conventional generators, and it is not entirely understood how this will affect the system at different wind power penetration levels. The simulation work presented in this paper evaluates the impact of the wind generation provision of these active power control strategies on a large, synchronous interconnection.

Synchrophasor-Based Auxiliary Controller to Enhance the Voltage Stability of a Distribution System With High Renewable Energy Penetration, *IEEE Transactions on Smart Grid*

Wind energy is highly location-dependent. Many desirable wind resources in North America are located in rural areas without direct access to the transmission grid. By connecting megawatt-scale wind turbines to the distribution system, the cost of building transmission facilities can be avoided and wind power supplied to consumers can be greatly increased; however, integrating megawatt-scale wind turbines on distribution feeders will impact the distribution feeder stability, especially voltage stability. This paper investigates the potential of using real-time measurements from distribution phasor measurement units for a new wind turbine generator control algorithm to stabilize the voltage deviation of a distribution feeder. The paper proposes a novel auxiliary coordinated-control approach based on a support vector machine predictor and a multiple-input and multiple-output model predictive control on linear time-invariant and linear time-variant systems.

Thermal Generation Flexibility With Ramping Costs and Hourly Demand Response in Stochastic Security-Constrained Scheduling of Variable Energy Sources, *IEEE Transactions on Power Systems*

This paper proposes stochastic day-ahead scheduling of electric power systems with flexible resources to manage the variability of renewable energy sources (RES). The flexible resources include thermal units with up-/down-ramping capabilities, energy storage, and hourly demand response. The Monte Carlo simulation is used in this paper to simulate random outages of generation units and transmission lines as well as represent hourly forecast errors of loads and RES. Numerical tests are conducted for a 6-bus system and a modified IEEE 118-bus system, and the results demonstrate the benefits of applying demand response as a viable option to manage RES variability in the least-cost stochastic power system operations.

Sensing, Measurement, and Forecasting Research

Direct Normal Irradiance Related Definitions and Applications: The Circumsolar Issue, *Solar Energy*

This paper provides a review of existing definitions related to direct normal irradiance (DNI) as well as a review of applications and measurement techniques of DNI. In addition, it offers expert consensus on clear definitions and terminology related to DNI and discusses the important role of circumsolar radiation in DNI.

A Method to Measure the Broadband Longwave Irradiance in the Terrestrial Direct Solar Beam, *Journal of Atmospheric and Solar-Terrestrial Physics*

This article describes a method to measure the broadband longwave irradiance in the terrestrial direct solar beam from 3 μm to 50 μm. The method might be used in developing calibration methods to address the mismatch between the broadband absolute cavity radiometers and shortwave radiometers and the lack of a daytime reference for pyrgeometer calibration. The authors used the described method to measure the irradiance from sunrise to sunset; the irradiance varied from approximately 1 W m−2 to 16 W m−2 with an estimated uncertainty of 1.46 W m−2, for a solar zenith angle range from 80° to 16°, respectively.

A Suite of Metrics for Assessing the Performance of Solar Power Forecasting, *Solar Energy*

Forecasting solar energy generation is a challenging task because of the variety of solar power systems and weather regimes encountered. Inaccurate forecasts can result in substantial economic losses and power system reliability issues. One of the key challenges is the unavailability of a consistent and robust set of metrics to measure the accuracy of a solar forecast. This paper presents a suite of generally applicable and value-based metrics for solar forecasting for a comprehensive set of scenarios (i.e., different time horizons, geographic locations, and applications) that were developed as part of the U.S. Department of Energy SunShot Initiative's efforts to improve the accuracy of solar forecasting. In addition, a comprehensive framework is developed to analyze the sensitivity of the proposed metrics to three types of solar forecasting improvements using a design-of-experiments methodology in conjunction with response surface, sensitivity analysis, and nonparametric statistical testing methods.

Joint Probability Distribution and Correlation Analysis of Wind and Solar Power Forecast Errors in the Western Interconnection, *Journal of Energy Engineering*

Wind and solar power generation differ from conventional power generation because of the variable and uncertain nature of their power output. This can have significant impacts on grid operations. Short-term forecasting of wind and solar power generation is uniquely helpful for planning the balance of supply and demand in the electric power system because it allows for a reduction in the uncertainty associated with their output. As a step toward assessing the simultaneous integration of large amounts of wind and solar power, this article investigates the spatial and temporal correlation between wind and solar power forecast errors.

Wind Power Ramp Event Forecasting Using a Stochastic Scenario Generation Method, *IEEE Transactions on Sustainable Energy*

Wind power ramp events (WPREs) have received increasing attention in recent years because they have the potential to impact the reliability of electric grid operations. In this paper, a novel WPRE forecasting method is proposed that is able to estimate the probability distributions of three important properties of the WPREs.

Wind Power Plant Model Validation Using Synchrophasor Measurements at the Point of Interconnection, *IEEE Transactions on Sustainable Energy*

Common practice in power system planning is to simulate a wind power plant (WPP) using a single-turbine representation. However, it is important to realize that the response of a single-turbine representation is not the response of an individual turbine; instead, it represents the collective behavior of a WPP. This paper presents experience in validating a WPP from available measured data. It investigates the discrepancies between the simulation results and the actual measurement, and it examines the probable causes of these discrepancies. The authors offer methods to validate the WPP dynamic model to better match the simulation results to the measured data. Understanding the nature of a WPP and the meaning of WPP equivalency is very important to determine the representation of a WPP.

[Recent Trends in Variable Generation Forecasting and Its Value to the Power System,] *IEEE Transactions on Sustainable Energy*

The rapid deployment of wind and solar energy generation systems has resulted in a need to better understand, predict, and manage variable generation. The uncertainty around wind and solar power forecasts is still viewed by the power industry as being quite high, and many barriers to forecast adoption by power system operators still remain. This paper discusses the recent trends in wind and solar power forecasting technologies in the United States, the role of forecasting in an evolving power system framework, and the benefits to intended forecast users.

Demand Forecasting in the Smart Grid Paradigm: Features and Challenges, *Electricity Journal*

Demand forecasting faces challenges that include a large volume of data an increasing number of factors that affect the demand profile, uncertainties in the generation profile of the distributed and renewable generation resources, and lack of historical data. A hierarchical demand forecasting framework can incorporate the new technologies, customer behaviors and preferences, and environmental factors.

The Wind Integration National Dataset (WIND) Toolkit, *Applied Energy*

Regional wind integration studies in the United States require detailed wind power output data at many locations to perform simulations of how the power system will operate under high-penetration scenarios. The wind data sets that serve as inputs into the study must realistically reflect the ramping characteristics, spatial and temporal correlations, and capacity factors of the simulated wind plants as well as be time synchronized with available load profiles. The Wind Integration National Dataset (WIND) Toolkit described in this article fulfills these requirements as the largest and most complete grid integration data set publicly available to date.

Comparison of Numerical Weather Prediction Based Deterministic and Probabilistic Wind Resource Assessment Methods, *Applied Energy*

Numerical weather prediction (NWP) models have been widely used for wind resource assessment. Model runs with higher spatial resolution are generally more accurate, yet they are extremely computationally expensive. An alternative approach is to use data generated by a low-resolution NWP model in conjunction with statistical methods. To analyze the accuracy and computational efficiency of different types of NWP-based wind resource assessment methods, this paper performs a comparison of three deterministic and probabilistic NWP-based wind resource assessment methodologies: (1) a coarse-resolution ($0.5° \times 0.67°$) global reanalysis data set, the Modern-Era Retrospective Analysis for Research and Applications (MERRA); (2) an analog ensemble methodology based on the MERRA, which provides both deterministic and probabilistic predictions; and (3) a fine-resolution (2-km) NWP data set, the Wind Integration National Dataset (WIND) Toolkit, based on the Weather Research and Forecasting model.

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NREL/BR-5D00-68667 • September 2018

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