NATIONAL RENEWABLE ENERGY LABORATORY

Grid Integration Science

NREL Power Systems Engineering Center • April 2017

NREL's Power Systems Engineering Center published 47 journal and magazine articles in the past year highlighting recent research in grid modernization. For information about these or 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.

Benjamin Kroposki, Ph.D., PE, FIEEE

Director, Power Systems Engineering Center

National Renewable Energy Laboratory

Integrated Devices and Systems Research

An Analytical Time-Domain Expression for the Net Ripple Produced by Parallel Interleaved Converters, *IEEE Transactions on Circuits and Systems II: Express Briefs*

This paper examines a time-domain expression that provides an exact representation of the summed and interleaved triangular waveforms, where the peak amplitude and parameters of the time-periodic component are all specified in closed form. The model is unique not only because it reveals a simple and intuitive expression for the net ripple but also because its derivation via modular arithmetic and Fourier series is distinct from prior approaches. The analytical framework is experimentally validated with a system of three parallel converters under time-varying operating conditions.

A Framework to Analyze the Stochastic Harmonics and Resonance of Wind Energy Grid Interconnection, *Energies*

This paper addresses a modeling and analysis methodology for investigating the stochastic harmonics and resonance concerns of wind power plants (WPPs). Wideband harmonics from modern wind turbines are observed to be stochastic, associated with real power production, and they may adversely interact with the grid impedance and cause unexpected harmonic resonance if not comprehensively addressed in planning and commissioning WPPs. This paper proposes a planning study framework that demonstrates a realistic benchmark system adapted from a WPP under development in Korea and discusses lessons learned through this research.

Ground Fault Overvoltage with Inverter-Interfaced Distributed Energy Resources, *IEEE Transactions on Power Delivery*

Ground fault overvoltage can occur in situations in which a four-wire distribution circuit is energized by an ungrounded voltage source during a single-phase-to-ground fault. The phenomenon is well-documented with ungrounded synchronous machines, but there is considerable discussion about whether inverters cause this phenomenon, and consequently whether inverters require effective grounding. This paper examines the overvoltages that can be supported by inverters during single-phase-to-ground faults via theory, simulation, and experiment; identifies the relevant physical mechanisms; quantifies expected levels of overvoltage; and makes recommendations for optimal mitigation.

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Synthesizing Virtual Oscillators to Control Islanded Inverters, *IEEE Transactions on Power Electronics*

Virtual oscillator control (VOC) is a decentralized control strategy for islanded microgrids where inverters are regulated to emulate the dynamics of weakly nonlinear oscillators. However, the nonlinear oscillators that are elemental to VOC cannot be designed with conventional linear-control methods. This study addresses this challenge by applying averaging- and perturbation-based nonlinear analysis methods to extract the sinusoidal steady-state and harmonic behavior of such oscillators.

Adaptive Hierarchical Voltage Control of a DFIG-Based Wind Power Plant for a Grid Fault, *IEEE Transactions on Smart Grid*

This paper proposes an adaptive hierarchical voltage control scheme of a doubly-fed induction generator (DFIG)-based wind power plant that can secure more reserve of reactive power in the WPP against a grid fault. Test results demonstrate that the scheme can improve the voltage support capability during the fault and suppress transient overvoltage after the fault clearance under scenarios of various system and fault conditions; therefore, it helps ensure grid resilience by supporting the voltage stability.

Adaptive Q-V Scheme for the Voltage Control of a DFIG-Based Wind Power Plant, *IEEE Transactions on Power Electronics*

Wind generators within a wind power plant (WPP) will produce different amounts of active power because of the wake effect; therefore, they have different reactive power capabilities. This paper proposes an adaptive reactive power-to-voltage (Q-V) scheme for the voltage control of a WPP based on doubly-fed induction generators.

Can Solar Save the Grid?, *IEEE Spectrum*

Photovoltaic (PV) systems installations in the United States have reached an installed capacity of more than 32 GW. The power they inject into distribution lines causes voltage- and frequency-control problems that threaten to destabilize the grid. But newer "smart" inverters can prevent a PV system from going off-line when it does not have to, making the grid *more* stable, according to recent research by NREL and its partners. NREL researchers have also been developing an innovative method for controlling inverters that will keep the grid stable even when all of the power is coming from solar, wind, and other forms of generation that connect to the grid via an inverter.

Dynamic Droop-Based Inertial Control of a Doubly-Fed Induction Generator, *IEEE Transactions on Sustainable Energy*

If a large disturbance occurs in an electric grid, two auxiliary loops for the inertial control of a wind turbine generator have been used: droop loop and rate-of-change-of-frequency loop. Because their gains are fixed, difficulties arise in determining them suitable for all grid and wind conditions. This paper proposes a dynamic droop-based inertial control scheme of a doubly-fed induction generator (DFIG). The scheme aims to improve the frequency nadir and ensure stable operation of a DFIG.

Effects of Power Reserve Control on Wind Turbine Structural Loading, *Wind Energy*

In this paper, the impact on the structural loads of a wind turbine providing power reserve is explored by performing a load suite analysis for several torque-based control strategies. Power reserve is required to provide those active power control services that enable the wind turbine to supply an increase in power. Researchers performed a load suite on a simulated model of a research turbine located at the National Wind Technology Center at the National Renewable Energy Laboratory. Results indicate that all power-reserve strategies tend to decrease extreme loads and increase pitch actuation. Fatigue loads tend to be reduced in faster winds and increased in slower winds, but they depend on the reserve-controller design.

Utilisation of Real-Scale Renewable Energy Test Facility for Validation of Generic Wind Turbine and Wind Power Plant Controller Models, *IET Renewable Power Generation*

This article presents an example of application of a modern test facility conceived for experiments regarding the integration of renewable energy in the power system. The capabilities of the test facility are used to validate dynamic simulation models of wind power plants and their controllers, based on standard and generic blocks.

Stable Short-Term Frequency Support Using Adaptive Gains for a DFIG-Based Wind Power Plant, *IEEE Transactions on Energy Conversion*

For the fixed-gain inertial control of wind power plants (WPPs), a large gain setting provides a large contribution to support system frequency control, but it may cause over-deceleration for a wind turbine generator that has a small amount of kinetic energy. Further, if the wind speed decreases during inertial control, even a small gain may cause over-deceleration. This paper proposes a stable inertial control scheme using adaptive gains for a WPP based on doubly-fed induction generators.

Slow Dynamics Model of Compressed Air Energy Storage and Battery Storage Technologies for Automatic Generation Control, *Energy Systems*

This paper presents a slow dynamics model for compressed air energy storage and battery storage technologies that can be used in automatic generation control studies to assess the system frequency response and quantify the benefits from storage technologies in providing regulation service. The paper also represents the slow dynamics model of the power system integrated with storage technologies in a complete state-space form.

Stable Adaptive Inertial Control of a Doubly-Fed Induction Generator, *Energy Systems*

This paper proposes a stable adaptive inertial control scheme of a doubly-fed induction generator. The proposed power reference is defined in two sections: the deceleration period and the acceleration period. The power reference in the deceleration period consists of a constant and the reference for maximum power point tracking operation. The latter contributes to preventing a second frequency dip (SFD) in this period because its reduction rate is large at the early stage of an event but quickly decreases with time. The results show that the scheme causes a small SFD while improving the frequency nadir and the rate of change of frequency in any wind conditions, even in a grid that has a high penetration of wind power.

Power System Design and Planning Research

Co-Optimization of Electricity Transmission and Generation Resources for Planning and Policy Analysis: Review of Concepts and Modeling Approaches, *Energy Systems*

The recognition of transmission's interaction with other resources has motivated the development of co-optimization methods to optimize transmission investment while simultaneously considering trade-offs with investments in electricity supply, demand, and storage resources. This paper describes co-optimization and provides an overview of approaches to co-optimizing transmission options, supply-side resources, demand-side resources, and natural gas pipelines.

Electricity Market Games: How Agent-Based Modeling Can Help under High Penetrations of Variable Generation, *Electricity Journal*

Integrating increasingly high levels of variable generation in U.S. electricity markets requires not only addressing power system and grid modeling challenges but also an understanding of how market participants react and adapt to them. Key elements of current and future wholesale power markets can be modeled using an agent-based approach, which may prove to be a useful paradigm for researchers studying and planning for power systems of the future.

Enabling Smart Grid Cosimulation Studies: Rapid Design and Development of the Technologies and Controls, *IEEE Electrification Magazine*

In the United States Energy Independence and Security Act of 2007, Title XIII sets the tenets for modernizing the electric grid through what is known as the "Smart Grid Initiative." This initiative calls for increased design, deployment, and integration of distributed energy resources, smart technologies and appliances, and advanced storage devices. The deployment of these new technologies requires rethinking and reengineering the traditional boundaries between different electric power system domains.

IGMS: An Integrated ISO-to-Appliance Scale Grid Modeling System, *IEEE Transactions on Smart Grid*

This paper describes the Integrated Grid Modeling System (IGMS), a novel electric power system modeling platform for integrated transmission-distribution analysis that co-simulates off-the-shelf tools on high-performance computing platforms to offer unprecedented resolution from independent system operator (ISO) markets down to appliances and other end uses. Specifically, the system simultaneously models hundreds or thousands of distribution systems in co-simulation with detailed ISO markets and automatic generation control-level reserve deployment.

The Impact of Wind Power on Electricity Prices, *Renewable Energy*

This paper investigates the impact of wind power on electricity prices using a production cost model of the Independent System Operator–New England power system. Different scenarios in terms of wind penetration, wind forecasts, and wind curtailment are modeled to analyze the impact of wind power on electricity prices for different wind penetration levels and for different levels of wind power visibility and controllability.

On Distributed PV Hosting Capacity Estimation, Sensitivity Study and Improvement, *IEEE Transactions on Sustainable Energy*

This paper first studies the estimated distributed photovoltaic (PV) hosting capacities of 17 utility distribution feeders using the Monte Carlo simulation-based stochastic analysis, and then analyzes the sensitivity of PV hosting capacity to both feeder and PV system characteristics. The approach is formulated as a mixed-integer nonlinear optimization problem, and a genetic algorithm is developed to obtain the solution. Multiple simulation cases are studied, and the effectiveness of the proposed approach on increasing PV hosting capacity is demonstrated.

Quantifying the Economic and Grid Reliability Impacts of Improved Wind Power Forecasting, *IEEE Transactions on Sustainable Energy*

This research quantifies the value of wind power forecasting improvements in the IEEE 118-bus test system, modified to emulate the generation mixes of the Midcontinent, California, and New England independent system operator balancing authority areas. The value of improved wind power forecasting was found to be strongly tied to the conventional generation mix, existence of energy storage devices, and the penetration level of wind energy. The simulation results demonstrate that wind power forecasting brings clear benefits to power systems operations.

Scheduling and Pricing for Expected Ramp Capability in Real-Time Power Markets, *IEEE Transactions on Power Systems*

Higher variable renewable generation penetrations are occurring throughout the world on different power systems. These resources increase the variability and uncertainty on the systems, which must be accommodated by an increase in the flexibility of the system resources to maintain reliability. This paper proposes scheduling and pricing methods that ensure expected ramps are met reliably, efficiently, and with associated prices based on true marginal costs that incentivize resources to do as directed by the market. Case studies show improvements with the new method.

The Value of Improved Wind Power Forecasting: Grid Flexibility Quantification, Ramp Capability Analysis, and Impacts of Electricity Market Operation Timescales, *Applied Energy*

This study analyzed the value of improving wind power forecasting accuracy at different electricity market operation timescales by simulating the IEEE 118-bus test system, modified to emulate the generation mixes of the Midcontinent, California, and New England independent system operator balancing authority areas. Simulation results showed that the generation resource mix plays a crucial role in evaluating the value of improved wind power forecasting at different timescales.

The Value of Day-Ahead Solar Power Forecasting Improvement, *Solar Energy*

In this paper, the value of day-ahead solar power forecasting improvements was analyzed by simulating the operation of the Independent System Operator–New England power system under a range of scenarios with varying solar power penetrations and solar power forecasting improvements. The results showed how the integration of solar power decreased operational electricity generation costs, by decreasing fuel and variable operation and maintenance costs while decreasing start-up and shutdown costs of fossil-fueled conventional generators.

Wholesale Electricity Market Design with Increasing Levels of Renewable Generation: Revenue Sufficiency and Long-Term Reliability, *Electricity Journal*

This paper discusses challenges that relate to assessing and properly incentivizing the resources necessary to ensure a reliable electricity system with growing penetrations of variable generation (VG). The study explores both traditional and evolving electricity market designs in the United States that aim to ensure resource adequacy and sufficient revenues to recover costs when those resources are needed for long-term reliability. Additionally, the study investigates how reliability needs may be evolving and discusses how variable generation may affect future electricity market designs.

Wind and Solar Energy Curtailment: A Review of International Experience, *IEEE Transactions on Smart Grid*

This paper proposes an adaptive hierarchical voltage control scheme of a doubly-fed induction generator (DFIG)-based wind power plant (WPP) that can secure more reserve of reactive power in the WPP against a grid fault. To achieve this, each DFIG controller employs an adaptive reactive power-to-voltage characteristic.

Enhancing Power System Operational Flexibility with Flexible Ramping Products: A Review, *IEEE Transactions on Industrial Informatics*

This paper presents an in-depth review of the modeling and implementation of flexible ramping products (FRPs). The major motivation is that although FRPs are widely discussed in the literature, it is still unclear to many how they can be incorporated into a co-optimization framework that includes energy and ancillary services. The concept and a definition of power system operational flexibility as well as the needs for FRPs are introduced.

Variability in Large-Scale Wind Power Generation, *Wind Energy*

The paper demonstrates the characteristics of wind power variability and net load variability in multiple power systems based on real data from multiple years. Demonstrated characteristics include probability distribution for different ramp durations, seasonal and diurnal variability and low net load events.

Stochastic Multi-Timescale Power System Operations with Variable Wind Generation, *IEEE Transactions on Power Systems*

This paper describes a novel set of stochastic unit commitment and economic dispatch models that consider stochastic loads and variable generation at multiple operational timescales. Comparative case studies with deterministic approaches are conducted in scenarios of low wind and high wind penetration levels to highlight the advantages of the proposed methodology, one with perfect forecasts and the other with current state-of-the-art but imperfect deterministic forecasts. The effectiveness of the proposed method is evaluated with sensitivity tests using both economic and reliability metrics to provide a broader view of its impact.

Wholesale Electricity Market Design with Increasing Levels of Renewable Generation: Incentivizing Flexibility in System Operations, *Electricity Journal*

This paper discusses the importance and challenges of incentivizing flexibility during short-term operations of the bulk power system due to the increasing variability and uncertainty from growing penetrations of variable generation. Operational flexibility can refer to many aspects of a resource's capability to support the power system, such as the speed, range, and duration of power output, as well as the ability to autonomously respond to frequency or voltage changes.

Power Systems Operations and Controls Research

Chance-Constrained System of Systems Based Operation of Power Systems, *IEEE Transactions on Power Systems*

In this paper, a chance-constrained system-of-systems-based decision-making approach is presented for stochastic scheduling of power systems encompassing active distribution grids. The proposed model is solved by using the analytical target cascading method, a distributed optimization algorithm in which only a limited amount of information is exchanged between collaborative independent system operators and distribution companies. A 6-bus and modified IEEE 118-bus power system are studied to show the effectiveness of the proposed algorithm.

Distributed MPC for Efficient Coordination of Storage and Renewable Energy Sources Across Control Areas, *IEEE Transactions on Smart Grid*

With increasing penetration levels of variable renewable generation, it is becoming increasingly important to take advantage of the capabilities of individual entities (and their areas) to balance variability. This paper employs and extends the approximate Newton directions method to optimally coordinate control areas by leveraging storage available in one area to balance variable resources in another area with only minimal information exchange among them.

Experimental Verification of an Energy Consumption Signal Tool for Operational Decision Support in an Office Building, *Automation and Construction*

This paper demonstrates an energy signal tool to assess the system-level and whole-building energy use of an office building in downtown Denver, Colorado. The energy signal tool uses a traffic light visualization to alert a building operator to energy use that is substantially different from expected. Practical discussion of the application is provided, along with additional findings from further investigating the significant difference between expected and actual energy consumption.

Measurement-Based Investigation of Inter- and Intra-Area Effects of Wind Power Plant Integration, *International Journal of Electrical Power and Energy Systems*

This paper has two objectives: the first is to analyze the general effects of wind power plant integration and the resulting displacement of conventional power plant inertia on power system stability, and the second is to demonstrate the efficacy of phasor measurement unit data in power system stability analyses, specifically when knowledge of the network is incomplete.

Optimal Power Flow Pursuit, *IEEE Transactions on Smart Grid*

This paper considers distribution networks featuring inverter-interfaced distributed energy resources, and develops distributed feedback controllers that continuously drive the inverter output powers to solutions of AC optimal power flow problems. The design of the control framework is based on suitable linear approximations of the AC power-flow equations as well as Lagrangian regularization methods. Overall, the proposed method allows the ability to bypass traditional hierarchical setups where feedback control and optimization operate at distinct timescales and to enable real-time optimization of distribution systems.

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

This paper considers future distribution networks featuring inverter-interfaced photovoltaic (PV) systems, and 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.

Scalable Optimization Methods for Distribution Networks with High PV Integration, *IEEE Transactions on Smart Grid*

This paper proposes a suite of algorithms to determine the active- and reactive-power set points for photovoltaic (PV) inverters in distribution networks. The objective is to optimize the operation of the distribution feeder according to a variety of performance objectives and ensure voltage regulation. The merits of the proposed approach are demonstrated with simulation results that utilize realistic PV-generation and load-profile data for illustrative distribution system test feeders.

Three-Stage Variability-Based Reserve Modifiers for Enhancing Flexibility Reserve Requirements under High Variable Generation Penetrations, *Electric Power Systems Research*

Historically, power system operators have held excess capacity during the commitment and dispatch process to allow the system to handle unforeseen load ramping events. As variable generation resources increase, sufficient flexibility scheduled in the system is required to ensure that system performance is not deteriorated in the presence of additional variability and uncertainty. This paper presents a systematic comparison of various flexibility reserve strategies. Several of them are implemented and applied in a common test system, and a three-stage reserve modifier algorithm is proposed and evaluated for its ability to improve system performance.

Transactive Home Energy Management Systems: The Impact of Their Proliferation on the Electric Grid, *IEEE Electrification Magazine*

Approximately 100 million single-family homes in the United States account for 36% of the electricity load, and often they determine the peak system load, especially on hot summer days when residential air-conditioning use is high. Traditional building power profiles are changing and are likely to change even more as residential energy storage products proliferate. Therefore, a better understanding of residential electricity demand is key to addressing the envisioned transition of the electric power system from its traditional structure to one that is transactive.

Sensing, Measurement, and Forecasting Research

A Data-Driven Method to Characterize Turbulence-Caused Uncertainty in Wind Power Generation, *Energy*

This paper explores a data-driven methodology that was developed to analyze how ambient and wake turbulence affect the power generation of wind turbine(s). Results show that (1) the turbine(s) generally produce more power under the in-wake scenario than under the out-of-wake scenario with the same wind speed, and (2) there is relatively more uncertainty in the power generation under the in-wake scenario than under the out-of-wake scenario.

Atmospheric Turbulence Affects Wind Turbine Nacelle Transfer Functions, *Wind Energy Science Discussions*

Nacelle-mounted anemometers have often been neglected because complex flows around the blades and nacelle interfere with their measurements. This work quantitatively explores the accuracy of and potential corrections to nacelle anemometer measurements to determine the degree to which they may be useful when corrected for these complex flows, particularly for calculating annual energy production in the absence of other meteorological data.

Fast All-Sky Radiation Model for Solar applications (FARMS): Algorithm and Performance Evaluation, *Solar Energy*

This study discusses the development of a fast all-sky radiation model for solar applications (FARMS) using the simplified clear-sky radiative transfer model, REST2, and simulated cloud transmittances and reflectances from the Rapid Radiation Transfer Model with a 16-stream discrete ordinates radiative transfer. Because of the complexity of solving the radiative transfer equation, the computation under cloudy conditions can be extremely time-consuming. This new radiative transfer model is more than 1,000 times faster than those currently utilized in solar resource assessment and forecasting because it does not explicitly solve the radiative transfer equation for each individual cloud condition.

Intercomparison of 51 Radiometers for Determining Global Horizontal Irradiance and Direct Normal Irradiance Measurements, *Solar Energy*

Accurate solar radiation measurements require properly installed and maintained radiometers with calibrations traceable to the World Radiometric Reference. This study analyzes the performance of 51 commercially available and prototype radiometers used for measuring global horizontal irradiances or direct normal irradiances. The intent of this paper is to present a general overview of each radiometer's performance based on the instrumentation and environmental conditions available at NREL.

Modeling Beam Attenuation in Solar Tower Plants using Common DNI Measurements, *Solar Energy*

Solar radiation reflected by concentrating mirrors is attenuated due to atmospheric extinction because it travels to the receiver of a solar tower plant. The lack of information on the magnitude of extinction increases the uncertainties in yield analysis and tower plant design. To overcome this absence of information, a model to derive the attenuation loss between heliostat and receiver from common direct normal irradiance (DNI) measurements was developed by Sengupta and Wagner (2011) (SW2011 model). This paper presents an updated version of that model and a comparison between the performance of the models using extinction measurements.

Probability Density Function Characterization for Aggregated Large-Scale Wind Power Based on Weibull Mixtures, *Energies*

This paper focuses on discussing Weibull mixtures to characterize the probability density function (PDF) for aggregated wind power generation. PDFs of wind power data are firstly classified attending to hourly and seasonal patterns. Results show that multi-Weibull models are more suitable to characterize aggregated wind power data because of the impact of distributed generation, variety of wind speed values, and wind power curtailment.

Radiometer Calibration Methods and Resulting Irradiance Differences, *Progress in Photovoltaics: Research and Applications*

Accurate solar radiation measured by radiometers depends on instrument performance specifications, installation method, calibration procedure, measurement conditions, maintenance practices, location, and environmental conditions. This study addresses the effect of different calibration methodologies and resulting differences provided by radiometric calibration service providers such as the National Renewable Energy Laboratory and manufacturers of radiometers.

Statistical and Clustering Analysis for Disturbances: A Case Study of Voltage Dips in Wind Farms, *IEEE Transactions on Power Delivery*

This paper proposes and evaluates an alternative statistical methodology to analyze a large number of voltage dips. The complete process is evaluated on real voltage dips collected in intense field-measurement campaigns carried out in a wind farm in Spain among different years. The results are included in this paper.

Wind Turbine Power Production and Annual Energy Production Depend on Atmospheric Stability and Turbulence, *Wind Energy Science Discussions*

This work provides guidelines for the use of stability and turbulence filters in segregating power curves to gain a clearer picture of the power performance of a turbine. The wind measurements upwind of the turbine include anemometers mounted on a 135-m meteorological tower and lidar vertical profiles.

NREL

National Renewable Energy Laboratory
15013 Denver West Parkway, Golden, CO 80401
303-275-3000 • www.nrel.gov

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

NREL/MP-5D00-68334 • April 2017

Prints on paper that contains recycled content.