



Functional Assessment of DFIG and PMSG-based Wind Turbines for Grid Support Applications

Final Project Report

S-73G

Power Systems Engineering Research Center
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Executive Summary

Wind turbines have massive rotating electrical generators that normally require full or partial coupling to the bulk power system using power electronic converters to control operation and the interconnection. A power system equipped with double-fed induction generators (DFIG) or with permanent magnet generators (PMSG) can have steady-state and transient performance that depends on specific control action and system dynamics. Therefore, the behavior of such controller has a critical role in system stability and dynamic performance of the power system. In addition, the power system is evolving toward a future with many interspersed and interconnected power-electronic based generators and loads. It is important to understand the role and impact of generators as the nature of the system changes. The inherent flexibility of power electronic systems makes them particularly useful in roles of active and reactive power management for grid support.

Although power converters play an important role in the overall performance and reliability of the electric power systems, it is not well understood how controller-influenced dynamics impact the power system. Furthermore, it is important to understand how to make the most use of wind-fueled generators and other power electronic resources to provide ancillary service in voltage and frequency control operations. This project investigates the ability for DFIG and PMSG wind turbines to provide service benefits by studying their theoretical capability and also performing experiments to test dynamics and observe mechanisms of the problem. After studying their capability for ancillary services, we propose a DFIG controller to add service of frequency response. Turbines with PMSGs may also benefit from a similar method. We also propose a DFIG configuration with grid-connected rotor windings to improve reactive power generation capability.

In particular, we find there are three main problems to consider:

1. There is misunderstanding of frequency response capability of DFIG wind turbines. Power electronic coupling is not always similar to full decoupling of frequency and voltage response from generator electromechanical dynamics. We consider the DFIG capability by removing influence of the controller and evaluating inertial response under assumptions of a low-inertia (DFIG-only, self-supporting) power system. We find the machine responds to a load-change in a stable manner and with rotor torque that draws upon stored rotational energy while the mechanical rotor and electrical frequency undergo dynamics. We find that the dynamics of the DFIG-only system give a baseline for developing a physics-based frequency and voltage response control law to provide a level of inherent stability. Linearized response of the DFIG to load transient shows useful ability for frequency response from the rotating turbine.
2. Controllers today are not well-suited for use in low-inertia power systems. In fact, a method of torque and reactive power control alone or even with added droop control might have negative impact on response when considering a low-inertia system. Torque and reactive power (TQ) control and droop-type methods are insufficient for ensuring a stable operation. Response should adapt to the changing load condition in magnitude and time. We propose a control which is derived from a physics-based model to provide inherent stability with response characteristic equations affected by the design choice and with response capability limited by parameters of the turbine and generator.

3. Reactive power capability from power electronic-connected devices is not clear since it depends on converter ratings and also parameters of the interconnecting device. For DFIG wind turbines, reactive power is generated or consumed by the machine-side converter of a back-to-back converter system. Filter inductors and generator windings consume some reactive power and can reduce the overall reactive power generation capability. RTE requires specifically that generators be able to provide reactive power capacity amounting to 1/3 of the nominal real power rating. It is not clear whether some generators can provide this, so this project investigates the capability of the DFIG for reactive power generation. Experiments are performed to illustrate the mechanisms and justify the ability for the converter-based reactive power capability. This project extends the approach and proposes a DFIG connection strategy that can shift the reactive power capability region toward more generation. The ability to provide reactive power consumption and generation even at low and no-wind speeds with full or partial coupling makes power electronic converters useful for reactive power ancillary services.

Power electronic converters have the ability to control the amount of resource being extracted for conversion to electric energy. The behavior of wind turbines with only torque and reactive power control during frequency excursion can be highly improved by advanced controls, especially in situations with low inertia. Frequency responsive controls have often been proposed in some form of a ‘droop’ or otherwise proportional control which can have the stabilizing effect. The problem is that they do not make a fulfilling use of the resource opportunity and their reliability depends heavily on the scenario. A load-responsive controller is needed to regulate frequency using rotor energy exchange and measured frequency change. This project proposes such controller with frequency and voltage control laws designed using a physics-based model under low-inertia assumptions. It provides a self-stabilizing frequency and voltage response that complements existing torque and reactive power control. The result is a tunable inertial frequency response due to load-change. Capability exists for the frequency and voltage to be maintained for sufficient duration (e.g. 50 % overload for greater than five seconds.) This means that dynamics of load-change can be managed and wind turbines can be used for reliable transient response.

Analytic evaluation of the wind turbine power systems is provided using standard steady-state and dynamic models. Boundaries of the reactive power capability are theorized considering generator parameters and converter and generator nameplate limits. Benefits are estimated for a surveyed set of generators. We find that not all generators exhibit benefit from the proposed rotor-tied configuration, and some show benefit in low-wind compared to high-wind operating conditions. We consider the stability of the DFIG power system using electromechanical dynamics to form transfer functions in the Laplace Domain. Characteristic equations are found to be influenced by power electronic controllers and generator parameters. We then derive a proportional plus integral (PI) control law that stabilizes frequency response due to load change. The proposed controller does not require communication or additional hardware. Rather, it adds a level of transient control not otherwise present. Flexibility of the control parameters spreads capability of the generator for specified depth and duration of response. Poles and zeros of the low-inertia system (i.e. DFIG only) can be specified to provide local stability. Coupled with external and slower primary and secondary controllers, distributed wind turbines can provide a level of frequency response to arrest load transients. A future with response categories and capability requirements can ensure stable long-duration operation.

Beyond theoretical expectation, we find experiments provide further and deeper insight to mechanisms behind the phenomena and lead to advanced understanding of the impact generators have on reliability and resiliency of the power system. A DFIG wind turbine test stand at the wind energy systems lab (WESL) at Iowa State University (ISU) lead to recent discovery of a new DFIG connection scheme that improves efficiency through reduced magnetic core loss. This project extends that work and shows improved value in reactive power generation as well. A PMSG test stand is also being built through this project to better understand the dynamics of PMSG wind turbines and their grid-interactive controllers. The DFIG and PMSG test equipment was useful in providing evidence of inertial response capability, reactive power configuration preference, and frequency control performance.

This work creates future opportunities for adding value to reactive power and frequency response capability. More fulfilled use of wind turbines relieves burden from other generators in the system. These added services from distributed or centralized wind plants could be used to replace auxiliary components like static-var compensators, synchronous condensers, and flywheels. With flexible controls, wind turbines could contribute to frequency and voltage response. They could also help fulfill spinning reserve requirements, or act as a motor load to enhance demand-response. The extended reactive power generation capability can afford added reactive consuming loads. The proposed self-stabilizing frequency control can reduce the frequency response provided elsewhere in the system.

Technical contributions of this project to the art of generator operation include these primary advances:

1. Deeper understanding of DFIG wind turbine frequency response capability of rotor mass, evidenced by a linearization of load-transient response considering a special low-inertia condition.
2. Realization that wind turbines with torque and reactive power control have a locally detrimental impact on frequency response, evidenced by a transient stability analysis considering effect of the DFIG controller in a self-supporting power system.
3. Development and derivation of a self-stabilizing frequency and voltage controller to provide transient response with tunable depth and duration, without added communication or hardware. Control law derivation and stability analysis provide mathematical basis for prescribing response.
4. A DFIG connection strategy that can make improved use of converter and generator nameplate current ratings. The alternative configuration results in a shift of the reactive power capability region; particular designs can benefit from added reactive generation capability. Bounds are equated to illustrate capability based on electrical parameters including resistance and inductance and provide basis for a preferred configuration.
5. Hardware test stands of DFIG and PMSG wind turbines and power electronic converters and controllers, demonstrating phenomena and verifying theory.

Project Publications:

- [1] N. David and Z. Wang, “Physical rotor inertia of DFIG wind turbines for short-term frequency regulation in low-inertia grids,” in *2017 IEEE General Meeting*, July 2017.
- [2] N. David and Z. Wang, “Rotor-tied configuration of DFIG wind turbines for improving reactive power support capability,” accepted for *2018 IEEE General Meeting*, August 2018.
- [3] N. David, Z. Wang, F. Xavier, and T. Prevost, “Fast frequency response by DFIG wind turbines for power systems with low physical inertia,” in revision, reviewed by *IEEE Transactions on Energy Conversion*.

Student Theses:

- [1] Nicholas David. *Availing grid support capabilities of wind turbine generators through configuration and control*, PhD Dissertation, Iowa State University, May 2019 (expected).