

Primary and Secondary Control for High Penetration Renewables

Future Grid Initiative White Paper

Power Systems Engineering Research Center

Empowering Minds to Engineer the Future Electric Energy System

Primary and Secondary Control for High Penetration Renewables

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White Paper Team

Christopher L. DeMarco Chaitanya A. Baone Yehui Han Bernie Lesieutre

University of Wisconsin-Madison

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Information about this white paper

For information about this white paper contact the corresponding author at:

Christopher L. DeMarco Professor Department of Electrical and Computer Engineering University of Wisconsin-Madison 2544 Engineering Hall 1415 Engineering Drive Madison, WI 53706 demarco@engr.wisc.edu; (608) 262-5546

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For additional information, contact:

Power Systems Engineering Research Center Arizona State University 527 Engineering Research Center Tempe, Arizona 85287-5706 Phone: 480-965-1643 Fax: 480-965-0745

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Executive Summary

As the U.S. and other nations prepare for electric power grid operation in which nontraditional renewable resources achieve high penetration, it is natural to also consider an increased role for these resources in the control functions of the grid. Traditionally, dynamic control of MW active power and frequency to regulate and stabilize the grid has been primarily implemented through the action of synchronous generator sets directly coupled to the network at 60 Hz. Their action is roughly classified into the categories of "primary control" (local, fast time-scale automatic feedback action) and "secondary control" (wider area, quasi-static control action on slower time scales). When compared to traditional turbine-driven synchronous generators, renewable generation, such as wind and photovoltaic sources, present very different electromechanical characteristics to the grid.

The intermittency of renewable sources has received wide attention in the research literature and the trade press. This paper will instead focus on other distinctions between renewables and traditional generation that are most relevant to the dynamics of control. These are: (i) modern renewable technologies are typically not "naturally" synchronous sources, locked to the 60 Hz of the grid; (ii) they therefore couple to the grid indirectly, through power electronic conversion; (iii) individual renewable generating sources are typically much smaller in MW capacity, and hence larger numbers of individual units contribute collectively. The future of the U.S. electric system will also see other smart grid power regulation technologies that will share some of these characteristics, including new forms of controllable energy storage and responsive load. In another relevant trend, the North American power system is also witnessing dramatic expansion of very high quality measurement and sensing technologies; at the bulk transmission scale, this trend is most evident in the wide deployment of "Phasor Measurement Units" (PMUs).

The trends above make it clear that opportunity and need exist for renewable resources to play a larger role in grid primary and secondary control. This white paper will argue strongly that best utilization requires control design tailored to the distinct dynamic characteristics and capabilities of renewables, rather than accepting design philosophies that seek to make the new technologies mimic the control behavior of traditional synchronous generators. In the formal terminology of control design, renewable generation can be viewed as a new class of control "actuators," and these new classes of hardware have very different bandwidth and saturation limits than those associated with traditional turbine-generator sets. Design techniques to utilize renewable generation in primary and secondary control should optimize within these bandwidth and operational limits, building on the established body of research in optimal control.

Optimal control was widely researched for power systems applications in the 1970's and 80's, but was largely discarded by the industry as impractical. However, this paper will argue that three decades of advances in algorithms, in embedded system computational power, and in high quality, high bandwidth PMU measurements, demand a revisiting of optimal control techniques. The high sampling rate and time synchronization of PMU measurements, combined with improved algorithms and computational hardware, open the door to *dynamic* observation of system state in the power grid, which is a prerequisite to state feedback optimal control designs. Dynamic state observation seeks to estimate

faster electromechanical *transient* behavior of the system, in contrast to the much slower *steady state* estimation that is common in today's system control centers.

While estimation of the full, grid-wide dynamic state remains difficult, such an ambitious goal is unnecessary to meet the objective of improved control for renewable generation. One need only estimate behavior of a small number of relevant electromechanical "modes" of the system, dramatically reducing the dimension of the estimation problem. As a practical consequence, a preliminary control design case study in this white paper will demonstrate that a renewable generator controller using just *one* remote PMU measurement, along with standard locally measured quantities, can significantly improve the quality of its control action. This optimal control based design tailors dynamics of the commands to the specific characteristics of bandwidth and actuation limits that are key to wind and photovoltaic renewables as control resources, and, as also illustrated in the case study, key to other smart grid technologies such as controllable storage.

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1 Introduction and Motivation

In the United States and throughout many parts of the world, installed capacity and energy production levels for electric generation from non-traditional renewable resources are growing rapidly. While appropriate characterizations of the footprint over which generation share should be calculated is an important question ([1], [2], [3]), reports suggest the high likelihood for periods during which production from wind turbines may account for more than 50% of total generation output over a significant electric service area. Installed capacity of solar powered generation is not yet as high as that for wind turbines, but declining costs and progress on several large solar projects around the world is raising the prospect that photovoltaic generation could also achieve significant percentage penetration in some parts of the U.S. Both wind turbines and photovoltaics present a range of interesting new challenges as they come to represent a larger share of the generator mix. Traditional synchronous generators driven by steam, water, or gas turbine prime movers have long dominated U.S. electricity production, and in many ways their characteristics implicitly underlie the philosophies of primary and secondary control practice for frequency and active power in the U.S. Among the goals of this paper will be to examine those aspects of existing control practice that are tied to characteristics of traditional generator technologies, and to consider how they may be impacted by potentially very different characteristics of new generation technologies for renewables. In keeping with the broad analysis objectives of this work, we wish to consider how much of existing practice reflects necessary and valuable grid control objectives, and how much is a pragmatic accommodation to technology specific characteristics of the hardware traditionally used for implementing this control. In those aspects for which goals of control can be clearly characterized independent of the technology of implementation, we will consider the degree to which renewable generation is suited to fulfill those control objectives. We wish to first establish the metrics by which we will measure performance, and then consider the capabilities of particular "regulating resources" (or, in the more precise terminology of control design, these "control actuators") to provide for this desired performance.

If increased penetration of renewable generation can be abstractly viewed as expanding a new class of control actuators in the power grid, in a complementary fashion, power system sensor and measurement technologies have also seen significant change in the last decade. In particular, the North American bulk power system has seen rapidly increasing penetration of Phasor Measurement Units (PMUs) [4]. From a control theoretic standpoint, a key aspect of PMU technology relative to traditional SCADA measurements is their much higher sampling/reporting rate and bandwidth. PMUs typically report at 30 or 60 times per second¹, versus SCADA systems that typically offered measurements at

¹ Basic Nyquist theory and PMU reporting rates might suggest a measurement bandwidth of 0-15 Hz or 0-30 Hz. More detailed examination of PMU specifications often reveals measurement sampling rates even higher than reporting rates. However, realistically accounting for non-ideal instrumentation transformers and filtering reduces the practical bandwidth considerably below the Nyquist-rate ideal. Exact characterization of measurement bandwidth will be PMU-hardware and installation-specific, but it is reasonable to assume that quality measurements with bandwidth up to 5 Hz are commonly achievable.

rates of only one sample per several seconds. This capability is further enhanced by the ability to very accurately align in time ("synchronize") measurements from widely separated geographic locations. Together, these capabilities offer a greatly enhanced ability to observe a high dimension vector of wide-area signals, over a much broader frequency-domain bandwidth. Significantly, PMUs allow wide-area measurement of signals over the band of frequencies most significant to power system electromechanical dynamics. By comparison, historic practice in the measurements used for primary and secondary control allowed only local measurements to have high bandwidth (indeed, often the only high bandwidth measurement was local frequency), while wide-area SCADA measurements had such low bandwidth that they could capture only quasisteady-state power grid behavior. Additional issues relating to communication latency, reliability, security and cost will of course influence the use of PMU-measured quantities in feedback design. However, the availability of PMU measurements makes the prospect of control utilizing multivariable system outputs over a wide geographic area much more viable than in the past.

While important progress on these topics has been made in prior research and in vendors' control technology implementations, many existing approaches are limited in the sense that they seek to force renewable generation to behave as much like traditional machines as possible. While in fairness one must recognize that such a design philosophy is partly a reflection of current standards, it is none-the-less a limitation widely reflected in research literature and on the part of the major wind turbine vendors. These works propose supplemental controls that attempt to mimic the inertial characteristics inherent to the physics of traditional synchronous machines (see, for examples, [5], [6], [7], [8], [9]). If this broad analysis paper is to make a useful contribution, we believe it must come by posing the question in a different fashion: (i) what are the objectives traditionally associated with primary and secondary control that are necessary to maintain stable secure operation of the power grid; and (ii) what control action on the part of high penetrations renewable generation can help meet these objectives?

2 The Case for Advanced Control Methodologies

The fundamental premise of this white paper is that for the greatest benefit of high penetration renewables to be realized, one must "open up" the design space of their control systems: do not tightly constrain these new classes of equipment to replicate old technologies (as in the inertial emulation approaches alluded to above), but rather seek to exploit the widely differing control characteristics of the diverse generation, storage and responsive load technologies that can contribute to the future U.S. power grid.

One aspect of this philosophy may be seen as an analogy to existing practices of voltage/VAR control, where there exists a long history of very different technologies contributing to the overall control objectives. Consider the classes of equipment that routinely contribute to voltage/VAR control: generator excitation systems, switched capacitors, tap-changing transformers, static Var compensators (SVCs), and, in the context of renewables, an increasing number of power electronic technologies such as D-VARs supplementing wind farms. In voltage control, the practice of dividing up control responsibility based on the size and speed of control action available from various devices is well accepted: large magnitude control actions from slow responding devices (e.g., large amounts "static" Vars, from switched capacitors), versus fast response from devices having limited magnitude control action (e.g., limited "dynamic" Vars, from exciters, or SVCs). While voltage/Var control is in some ways simpler than active power/frequency control, due to the quasi-static and relatively localized nature of voltage response, Var control has traditionally made greater use of a more varied suite of "actuators."

Our premise here is that growth of new technologies available to contribute to frequency/active power control (power electronic coupled renewables, responsive load, storage) will bring similar features. As will be explored in greater detail in the case study to follow, perhaps the most obvious analogy exists if one considers coordinating active power control from a wind turbine with that of a battery storage unit. For simplicity, consider blade pitch control as a means of varying the mechanical power input to a wind turbine for a given wind speed (note: newer technologies may achieve variation in mechanical power output by varying rotation speed, and hence aerodynamic power conversion efficiency). First, to have available both positive and negative incremental changes in power, one must assume that the machine is operating at least slightly below its maximum power output point (i.e., it is "spilling wind"). Clearly then, the range of available blade pitch motion has hard limits in both directions, and any attempt to use this action for primary frequency control must respect these limits. Moreover, to maintain low stress on the drive train, any control action requested of blade pitch must be of very low bandwidth. Suppose therefore that the wind machine's control of active power is supplemented by a very modest amount of battery storage. Existing work in the research literature has already recognized that storage as a supplement could be used to reduce drive train stress [10]. However, from a more general control systems viewpoint of loop shaping, one might consider using the power output of the battery to extend the bandwidth of the wind turbine's actuation. That is, viewed as an actuator in the frequency domain, the Bode plot of the wind turbine has a low pass filter transfer characteristic,

from the commanded power change as actuator input, to the achieved change in electrical power as actuator output. An appropriate role for a supplemental control action, whether from a battery or other source, is to extend the effective frequency range of actuation. In a simple block diagram view, the parallel connection of wind turbine actuator and the supplemental actuator produce a transfer characteristic with a higher cut-off frequency. While we wish to stress that a range of other technologies could play this supplemental control role, the reader may note that a high-pass frequency characteristic is well suited to the capabilities obtained from modest sized battery storage. Viewed as an actuator taking commanded power as input, and grid delivered electrical power as output, the battery would have zero dc gain; indeed, it could have zero gain below the cut-off frequency of the wind turbine's control characteristic. Therefore, the battery would never be asked to provide or absorb steady state power. With suitable sizing of the battery relative to the cut-off frequency, a band limited, predominantly high-pass control design inherently respects the charge/discharge limits of the battery.

Advances in control system design over the last several decades open the door to much more sophisticated approaches than the simple loop shaping argument described above. The specific characteristics of wind generation and battery storage used to illustrate the point above are also used in the case study example of Sections 4 and 5. However, we wish to stress that the point of this white paper is to promote a broader control design philosophy. In particular, our premise that future grid control design require techniques that respect differing bandwidth and saturation limits for diverse technologies that may contribute to active power/frequency control on the grid. While the control optimization problems will certainly be challenging, they may in some ways be more tractable than those in voltage/Var control. Most active power control actions are continuous, in contrast to the discrete switching action inherent in switched capacitor banks and tap changing transformers. The analytic tools of optimal control [11], and more recent advances based on convex optimization [12], hold great promise for active power/frequency control to facilitate high penetration renewables.

To close this section, it is worthwhile to note the history of optimal control theory in the literature on generation control in the 1970's and early 80's. Beginning from Elgerd's classic 1970 paper [13], a number of authors demonstrated the potential for improved performance that could be obtained in applying optimal control designs to generator governors and AGC ([14]-[16]). The drawbacks in these approaches were almost entirely related to practical limitations in the implementation. Most methods required dynamic observation of system states (note: NOT the more familiar quasi-static state estimation common in power system control centers). Because dynamic recovery of states from measurements typically requires non-local information for observability, and because measurement bandwidth must encompass the natural frequencies of the system, such capabilities were beyond the reach of 1970's and 80's grid sensor technologies. However, as previously described, the proliferation of high bandwidth PMU measurements shows excellent potential to overcome exactly these limitations. When coupled with tremendous advance in computational power to implement advanced control and estimation algorithms, and more than twenty years of refinement in the algorithms themselves, we believe the time is ripe to revisit optimal control applications in primary and secondary control. Indeed, we argue that such techniques may be key to allowing high penetration renewables to fully contribute to grid control objectives.

3 The Roles of Inertial Response, Primary Control and Secondary Control: Past and Future

The North American electric power grid is a complex system, displaying dynamic electromechanical coupling on a nearly continental scale. Among its key output variables that reflect underlying electromechanical dynamics are those of electrical frequencies. At locations with synchronous generation attached, the inherent physics of the synchronous machine dictate that electrical frequency of the generator voltage and mechanical rotational speed of the generator are locked in fixed proportion to one another, so that variation of frequency at these locations directly reflects deviations in rotational speed away from the desired steady state. Moreover, the nature of AC power transmission is such that a synchronous region is in exact equilibrium only if electrical frequency is equal at every node in the network; i.e. all interconnected generators rotating at the same (normalized) speed. In these basic facts, two related facets of an underlying grid control problem present themselves: (i) the requirement for stable dynamic performance, such that any deviation of the (dynamically) independent frequencies of generators all return in a stable fashion to steady state; and (ii) the quasi-steady state regulation requirement, that the shared synchronous frequency (equal at all nodes in equilibrium) be regulated to a tight band about its desired 60 Hz value. At risk of oversimplifying the more detailed material to follow below, one may summarize: inertial response contributes mostly to stable dynamic response; secondary control contributes mostly to the quasi-steady state maintenance of the common area-wide frequency within desired bounds, and primary control spans these two requirements.

The overall requirement for stably regulating frequency within a tight range reflects the objective to reliably maintain the instantaneous balance between generation and load. This is accomplished by ensuring that adequate resources are available to respond to expected and unexpected imbalances and restore frequency to its scheduled value in order to ensure uninterrupted electric supply. The inertia of traditional synchronous generators plays a significant role in maintaining the stability of the power system during a transient scenario. The inertia dictates how large the frequency deviations would be due to a sudden change in the generation and load power balance, and influences the eigenvalues and vectors that determine the stability and mode shape of transient response. The larger the inertia, the smaller will be the rate of change in rotor speed of the generator during an imbalance in power. This type of response of the traditional synchronous generators is called inertial response. This is a synchronous machine's "reaction," inherently dictated by rotational Newton's law, to sudden changes in the balance between applied mechanical shaft power and electrical power extracted at the generator terminals. Beyond this inherent response due to the laws of physics, typical design and operational practice may add additional response characteristics. The mechanical shaft power of a turbine prime mover is typically designed to change in response to power imbalance (as reflected in measured speed or frequency change), through external control loops called governor controls. Governor control systems change the fuel supply to the turbine in response to a change in generator speed, thereby controlling the generated power and thus regulating the changes in frequency. This type of control is traditionally called "primary" frequency control. While it may vary with the characteristics of a specific hardware, the time scale of this control is from about half a second to a minute. Control actions of older turbine governors have low bandwidth because of limitations on the mechanical systems that must physically move in response to its commands (e.g., gas/ steam/water flow valves). Improved "fast valving" technologies can be interpreted in the control systems context as a means to extend actuator bandwidth.

As noted in the introduction, wind and photovoltaic generation sources are expanding rapidly in the U.S. Increasing penetration of these renewable generation sources inevitably poses new technical challenges to the reliable and secure operation of the electric grid. Some of these challenges are inherently due to the intermittent nature of the weather-based drivers for such generation: insolation and wind. Others are associated with the technologies that interface these sources to the grid. The low voltage, DC current/voltage production of photovoltaic panels require that they be integrated to the electrical grid through power electronic-based converters, to transform the low voltage DC production to higher AC voltages compatible with grid standards. Most new wind turbine generator designs (i.e., so-called "Type-3" and Type-4" systems) are similar in the sense that part or all of their active power production is delivered to the grid through power electronic converters. With the power electronics decoupling primary source current and voltage from grid current and voltage, the electrical terminal characteristics and dynamics of these sources differ significantly from those of conventional synchronous generators. These changes in dynamic terminal characteristics raise challenges in regard to their impact on the electromechanical stability of the grid, but may also offer flexibility in the potential of these resources to contribute to grid control.

Among several available wind generation technologies, variable speed wind turbines utilizing doubly-fed induction generators (DFIGs) are gaining wide spread acceptance. The main advantage of DFIGs as compared to conventional fixed speed wind turbine generators is their higher efficiency. This higher efficiency is achieved in large part through the ability of DFIGs to operate near their optimal turbine efficiency over a wider range of wind speeds, through variable speed operation. Such variable speed operation is made possible through back-to-back AC/DC/AC power electronic converters. However, in doing so, the wind turbine's rotational inertia is not coupled to its electrical terminal characteristics in the fashion of a traditional turbine/synchronous-machine generator set. If a power electronically coupled generation source directly substitutes for a synchronous machine generation source, without compensating control, this reduces the inertial response to supply/demand mismatch in the grid. Several studies have looked at the impact of this reduction in system inertia due to the increasing penetration of wind generation on grid frequency regulation ([3], [17], [18], [19]). As the penetration of wind is expected to grow dramatically in the coming decade, researchers and vendors have sought improved designs to allow these technologies to better contribute to grid frequency regulation and stability. As noted above, most of the solutions proposed to date seek to mimic the inherent inertial response of traditional synchronous generators; i.e., they add a control loop that incrementally feeds or draws active power in response to a decline or rise in the time derivative of frequency. The control power required by this proposed additional loop comes predominantly either by varying the mechanical input power to a wind turbine, through change in its blade pitch or nominal rotational speed, or by drawing/feeding additional active power from/to the grid through the rotor side converter². However, these solutions neglect two key limitations in such implementations: bandwidth and saturation limits on the actuators. Any control loop designed to artificially mimic the effect of inertia inherent in Newton's law will inevitably be limited both in bandwidth, and in the magnitude of power change that can be applied.

The issues associated with generation via photovoltaic panels are similar, and perhaps more pronounced. As noted above, the electrical output from a photovoltaic cell is a low voltage, DC quantity; for maximum efficiency at different levels of isolation, the voltage output must be allowed to vary over a range of values to track the maximum power output point. The power electronic converters that couple directly to the solar panel are typically designed to keep the panel at its maximum efficiency by regulating the DC voltage at its terminals; a further step of power electronic conversion then takes the DC power output of multiple panels and couples it the AC voltages and current at the grid interface point. This physics of this production process of course involves no rotating sources, and indeed, offers no significant short-term energy storage mechanism analogous to the inertia of a traditional synchronous generator³. Hence, without compensating technologies, increasing penetration of photovoltaic generation sources will create even more significant reductions in effective inertia on the bulk electric grid.

Large-scale energy storage technologies such as batteries, high-speed flywheels and electro-chemical capacitors are currently being researched, developed and deployed for grid applications [20]. Storage applications can be loosely divided into power applications and energy management applications, which are differentiated based on the storage/discharge durations. Technologies used for power applications are used for short discharge durations, ranging from fractions of a second to few minutes. Technologies used for energy management applications store excess energy during periods of low demand for use during periods of high demand. These devices are typically used for longer discharge durations exceeding one hour, to serve functions that include reducing peak load and reducing generation variability to help integration of renewable generation into the grid. Our focus here will be on short duration storage technologies that can be used to provide control power during transients and assist in primary frequency control. Storage technologies that suit such applications, typically grid scale batteries, can respond at a much faster rate than the mechanical actions of traditional governor controls and blade pitch or wind turbine speed control mechanisms. However, economic concerns suggest that such storage will be very limited in the amount of power it can provide.

In this context, one challenge posed to primary frequency control will be regulate changes in frequency due to disturbances such as variations in incident wind power or insolation, on a time scales of a few seconds. From a multi-input/multi-out control system design standpoint, key questions center on the ability of the system's sensors and actuators to observe and control the variations in system frequency that will result from such stochastic variations in incident source power. In terms of the measurement and control architecture, one must ask whether it is reasonable that responsibility to provide

² Power electronic converters typically include energy storage associated with capacitors on their internal DC bus. However, in most designs the stored energy that may practically be drawn from this source is very small in comparison to the stored energy available from inertia of a typical synchronous generator.

³ Again, the power electronic converter may provide a very small amount of storage in DC bus capacitors.

this primary control fall exclusively on traditional turbine/synchronous-machine generator sets, when their percentage of the overall generation mix may be declining, and renewable sources are growing as a percentage of generation fleet. A potential answer lies in having the renewable generation sources themselves to contribute to regulation; advancement of other aspects of Smart Grid technology and actions by FERC are also likely to provide incentives for regulation service provision from storage technologies and controllable responsive load. In the control terminology emphasized above, one must characterize the transfer characteristics of available actuators. Such characterizations should focus on two crucial aspects of performance: bandwidth and saturation limits.

In examining new technologies associated with renewable generation (most clearly wind turbines) and with new electrical storage technologies (most clearly batteries and flywheels), complementary saturation and bandwidth limitations seem guite natural. In particular, our hypothesis here is that a re-thinking of primary control might profitably begin from considering two broad classes of actuators: (i) low bandwidth, "slow" actuators with broad saturation limits (e.g., power control available by varying blade pitch in wind generators, or from traditional governor controls in synchronous generators) and (ii) high bandwidth, "faster" actuators with narrow saturation limits (e.g., power control available from battery or flywheel energy storage). With such a characterization, one may formulate the problem in the context of multi-input control objective, that of stable regulation of grid frequency during disturbances. Coupled with the broader bandwidth of wide area measurements becoming available from PMUs, it becomes feasible to consider distributed, observer-based control methods. In particular, each local controller may be equipped with a dynamic state observer that utilizes locally available measurement signals, along with some modest number of remote PMU measurement signals, to form a state estimate that is then fed to its local controller. Each actuator that contributes frequency regulation, whether it be a wind turbine, a battery, or a responsive load, is given an input command from its local controller, but these local controllers should be designed in a coordinated fashion to contribute to system-wide objectives. The primary control objective is regulate system frequency in the face disturbances, whether these be stochastic variations in wind power, in photovoltaic insolation power, random variation in load demand, or unanticipated equipment switching or failures. As noted previously, the broader measurement bandwidth of PMUs allows them to observe power system dynamics that were difficult/expensive to capture with earlier measurement technologies. They provide a direct measure of the voltage and current phase angles. This, coupled with their high measurement rate, means that voltage angle measurements can be used directly in power system operations and control. However, the value of such measurements in any control scheme must be weighed against the still significant cost of providing highly secure, highly reliable, low-latency communication over long distances.

3.1 Frequency Regulation in Power Systems

Maintaining the frequency at its target value requires that the active power produced and/or consumed be controlled to keep the load and generation in equilibrium. "Headroom" of quickly achievable active power variation, usually called frequency control reserve, is kept available to perform this control. The positive frequency control reserve designates the active power reserve used to compensate for a drop in frequency. Deployment of negative frequency control reserve serves to decrease the frequency. Frequency control in power systems is undertaken at roughly two levels and time-frames, commonly referred to as primary control and secondary control ([21][22][23][24]).

The term of "primary" frequency control is traditionally reserved for local, automatic control action that adjusts the active power output of the generating units in direct response to measured frequency variations [23], [24], and with the indirect impact of restoring balance between load and generation. Its design should be chosen to achieve its regulation objective in a stable fashion following large generation or load disturbances. It important both for the quasi-steady state objective of regulating frequency to setpoint, and for dynamic objective of maintaining electromechanical stability of the system.

To put this impact on dynamics in perspective, it is useful to review the basic equations governing electromechanical behavior of the power grid. The well-known swing equations govern rotational speed/frequency of synchronous generators in a power system. For a generator indexed by k, let ω_k denote the machine's electrical frequency (which must be exactly proportional to its mechanical speed, with constant of proportionality set by the number of generator windings); $\Delta \omega_k$ denotes its deviation away from the synchronous value. Then the time derivative of frequency (proportional to the rotational acceleration) is governed by an equation of the form:

$$\begin{split} \Delta \dot{\omega_k} &= M^{-1} (\Delta P_{mech} - \Delta P_{elec}(\underline{\delta})) \\ \Delta \dot{\delta_k} &= \Delta \omega_k \end{split}$$

 P_{mech} - mechanical shaft power input to the generator,

 P_{elec} - electrical power output of the generator,

 δ_k - voltage angle at the generator bus,

 $\underline{\delta}$ - vector of all the system bus voltage angles.

Here we adopt standard notation, with a "dot" over a quantity indicating its first derivative with respect to time. An observant reader may ask why the right hand side of the acceleration equation above has units of power, instead of the units of torque normally associated with the rotational form of Newton's law. The answer lies in the implicit assumption of successful frequency regulation: if one assumes that frequency (and hence rotational speed) is well regulated, and recalls that power equals torque times speed, power is becomes (almost) exactly proportional to torque. The remaining approximation relates to the very low losses in grid-scale electrical generators, and their high electromechanical conversion efficiency (not to be confused with the much lower thermal efficiency). The electrical power delivered to the network is almost exactly equal to the power associated with magnetic fields within the machine; that is, the torque opposing motion due to the windings' magnetic field interactions is (within a few percent) equal to electrical power delivered divided by rotational speed. The result is that a synchronous machine's rotational acceleration is driven by the difference of applied shaft power from the prime mover "in," less electrical power delivered from its terminals to the network "out." When mechanical power in matches electrical power out, a synchronous machine operates in steady state at constant speed.

A "droop" governor control is a simple proportional feedback that modifies mechanical power input in (negative) proportion to speed error. Given the exact proprotionality of speed and electrical frequency inherent in a synchronous machine, with suitable normalization this effect is captured by adding a term linear in frequency error to the swing equation above, yielding:

$$\Delta \dot{\omega_k} = M^{-1} (\Delta P_{mech} - \Delta P_{elec}(\underline{\delta}) - g \Delta \omega_k).$$

Some reasonable percentage of (but not all) generators in a synchronous area may be expected to be fitted speed governors to perform this control automatically; i.e., to be contributors to primary frequency control. Primary control is commonly exercised through continuously acting turbine governors, with relatively fast operating time scale of seconds. On this time scale, it provides a (but not the exclusive) contribution to maintenance of acceptable quasi-steady state operation, but must also meet the dynamic requirement of keeping transient response stable. As instantaneous load power from the system varies with customer demand, any imbalance drives a change in frequency, which participating governors then counteract through feedback action. Such primary governor controls respond to frequency by varying generators' real power output are almost always local to the individual power plants. The direct feedback term (the "droop") is independent of any centralized control signal, being based just on the local measurement of the generator's rotational speed or terminal electrical frequency. However, the proportional feedback gain/droop values may be selected (and perhaps periodically updated) based on wider area concerns for stable sharing of response among multiple units. Moreover, a setpoint input to the control loop may also be centrally determined, and can be supplemented by higher level (but more slowly varying) signals that reflect the secondary control objectives to be described below.

Secondary frequency control operates from a more centralized system perspective, on a slower time scale. It is a wide area control that adjusts the active power production of generators, with the mixed objective of further contributing to restoration of frequency to desired steady-state (60 Hz in North America), and also to restore interchanges on monitored tie-lines between areas to their target values following an imbalance [25]. Ideally, the generators within an area where demand versus production imbalance has occurred experience the largest frequency change in response to this imbalance, and therefore respond most actively to modify their power output via control action. By

design and operational agreement, defined "Balancing Authorities" each seek to maintain load and generation balance within an area. From a block diagram perspective, secondary control may be seen as acting to update target setpoints "feeding" the individual generators' primary control loops, thereby better managing sharing of power production among the many generators within an area. Without secondary control, the relative size of power output change from various generators is set by relative droop constants/proportional feedback gains in the primary control; relying on the droop constants alone would not be sufficiently flexible for economically optimal sharing of output among generators, and would of course exclude from participation any machine not contributing to primary control. This allocation of power production between different buses within the transmission network also provides a mechanism by which loadings of transmission lines can be indirectly managed. However, the reader should note that the number of degrees of control freedom, generator outputs, will typically be fewer than all the possible transmission lines on which one might wish to regulate flow; hence the secondary control typically limits its action to a few key monitored tie-lines. The maintenance of the desired balance of production among multiple generators, over a relatively slower time scale of minutes, is the role of secondary control.

As described above, primary control is inevitably a closed loop feedback, fully automated. In contrast to this, the slower time scale of secondary controls are such that human intervention and supervision is at least possible, though modern practice tends to automate these processes also. It is the primary control that acts on time scales comparable to those of the electromechanical dynamics of interconnected synchronous generators, and therefore it is primary control that most impacts grid stability.

Maintenance of balance between production and demand is usually enforced within a geographically and electrically contiguous region known as a Balancing Authority; such an area will comprise a set of buses with intercommunicating measurements and telemetry [26]. Such an area is responsible for regulating its production to maintain its interchange schedule with adjacent areas, while simultaneously contributing to frequency regulation. For multi-area interconnected systems, these two objectives are combined in a weighted fashion as a single numeric measure, the "Area Control Error" (ACE). The ACE for a given area is the weighted sum of the deviation away from setpoint of power flow on monitored tie lines, with a term proportional to system frequency deviation given as

$$ACE = \beta \Delta f + \sum \Delta P_{tie}$$

where β is the power-frequency characteristic of the zone under consideration, Δf is an area-wide measure of frequency deviation from setpoint, and ΔP_{tie} is the interchange flow deviation from the scheduled value. Two Control Performance Standards, CPS1 and CPS2, have been defined by the North American Electric Reliability Corporation (NERC) [27] to assess an area's ACE. Their purpose is to indicate whether an area's generation is adequately controlled to make interchange meet its schedule and interconnection frequency support obligation. CPS1 measures ACE variability, a measure of short-term error between load and generation. It measures control performance by

comparing how well a Balancing Authority's ACE performs in conjunction with the frequency error of the interconnection. CPS2 involves ten-minute averages assembled from ACE.

3.2 Frequency Regulation with Emerging Grid Technologies

As previously observed, the impact of increasing penetration of wind energy generation on electric grid electromechanical stability is a topic of growing concern in power engineering practice, and has motivated study of improved control designs for alternative energy sources such as wind. Until recently, wind energy sources were among the class of generators not selected to contribute to primary control, nor to electromechanical control in general. While it is accepted operating practice in power systems that only a subset of generators will exercise governor control, from a control perspective, any plant not contributing to primary control is in a sense a "free rider" on the governor action provided by those generating plants that do [27]. However, recall that the synchronous machine swing equation previously described is simply a rotational form of Netwon's law, and hence, even without governor action, a traditional synchronous machine slows the time rate of change of frequency by virtue of its inertia. The larger the inertia, the smaller the time rate of change of frequency for a given MW imbalance between that generator's mechanical power "in" and the electrical power "out." In the widely utilized Doubly Fed Induction Generator (DFIG) wind turbine designs, several differences present themselves. First, because the electrical generator is an induction rather than synchronous machine, the governing electromechanical equations do not enforce exact proportionality between electrical frequency and rotational speed. In the terminology of electrical machine design, an induction machine has "slip" between its rotational speed and electrical frequency. Independent of power electronic coupling effects, this alone lessens any inertial effect. Moreover, as its "doubly fed" title suggests, a DFIG has two electrical paths feeding from the generator to the grid. A portion of the generator's electrical power output passes through power electronics that further decouple grid frequency from generator frequency. As a result, a DFIG's coupling of rotational speed to system frequency, and the resulting inertial response, is very weak unless enhanced explicitly by control design. In an inertia mimicking scheme, a control signal proportional to the rate of change of bus frequency is fed through the external control loop, thereby drawing/feeding additional electrical power from/to the network in response to an increase/decrease in the derivative of frequency. The gain constant between measured frequency derivative and change in power plays the role of inertia. However, true physical inertia, as it appears in the rotational form of Newton's law for a synchronous machine, has infinite bandwidth and has no actuation limit (up to the point of breaking turbine shafts). In contrast, an engineered induction machine/power electronics control scheme that seeks to mimic this effect inevitably has response bandwidth limitations. Moreover, practical implementations of such schemes will typically filter and "smooth" the commanded power change, to lessen stress on the drive-train, further limiting bandwidth. Finally, such schemes must take into account the limits on the ratings of the power electronic converter, which bound how large a change in current/power can be commanded. These inevitable limits on bandwidth and power change imply that any inertia-emulating scheme must inevitably fall short of replicating inertia, which as a law of physics have infinite bandwidth and no limits on rotational power/torque. These observations are not intended to be excessively critical of inertial emulation, which is an appealing intuitive approach to design. Rather, this discussion is meant to suggest that design methodologies that explicitly consider bandwidth and saturation limits offer the possibility for significant improvement.

Illustrating the impact of reduced inertial contribution from DFIG designs, in [28], the authors conclude that unlike with fixed-speed wind turbines, DFIG wind turbines replacing synchronous generators reduce the frequency nadir after a loss of generation. They attribute this outcome to the negligible inherent inertial response of DFIG wind turbine generators. A supplementary control loop that yields an inertia-like response in DFIG generators is proposed. In [29], it is shown that through the addition of such a supplementary control loop, an inertial response characteristic can be added to wind turbines. From a control system design perspective, if rotational speed/electrical frequency error is the measured output of interest, an inertial term is simply derivative feedback; recall the earlier observation that droop governor control is simply a proportional feedback on frequency error. Textbook results of classical control theory suggest that proportional/derivative feedback rarely yields an optimal scheme for a high order, lightly damped systems (such as the power grid). And again, classical control design dictates that low pass filtering be added to limit the bandwidth over which the controller behaves like a differentiator, to avoid performance problems associated with noise and high frequency disturbances.

In [17], the authors demonstrate a modification to the torque control loop of the wind system by having an additional control loop that reflects inertial emulation. In [30], the authors propose a method utilizing stored kinetic energy in the wind turbine blades to emulate synchronous machine inertial response by having additional control paths. Within the problem of frequency control, the inertial response is discussed in [31]. Two different additional control loops have been evaluated and it has been shown that both limit the drop in frequency after a disturbance. In their inertial emulation scheme, the authors of [31] add a low-pass filter in front of the proportional inertia constant block to restrict the stress on the drive train of the wind turbine system. In the other scheme, they consider a simple proportional controller to emulate a traditional droop controller. In this scheme, the additional/deficit control power comes from changing the blade pitch of the wind turbine. They do not construct an optimal controller that would limit the stress on the drive train due to sudden changes in turbine speed. Changing the blade pitch is clearly a mechanical action involving very large moving masses; the stress on the turbine blades during such transient conditions must not be allowed to be large. Again, the bandwidth limitation of this actuator (blade pitch control mechanism) is not considered in the design of the controller. Other ideas of inertial emulation can be found in references [32] - [35]. While the idea of inertial emulation is intuitively appealing, it may be significantly handicapped by the bandwidth and saturation limitations of the additional control loop. The results presented in [27] raise several concerns regarding the effectiveness of inertial emulating control for wind turbines.

In addition to from adding control systems on the wind turbine itself, various strategies have been proposed for frequency regulation in power systems with wind power using supplemental energy storage systems, such as batteries, superconducting magnetic energy storage (SMES), flywheels and others. In [36], the authors assess the impact of installed wind power generation and battery on the system frequency. They demonstrate that in a two-area power system, the tie line power fluctuation as well as the system frequency fluctuation is high. They show that the installed battery can suppress these fluctuations and that the effectiveness of battery suppression of these fluctuations depends on battery capacity. They do not consider the power/energy limitations of a battery in their control scheme. In [37], the authors propose a scheme with a SMES system close to the wind generator. The role of the SMES system is to smoothen the short-term fluctuations in wind farms. They consider two control loops: one is the wind power controller and the other is the SMES controller. They model the wind controller using a high-pass filter and the SMES controller as a low-pass filter. Again here they do not consider the saturation limits of the SMES system and the bandwidth limits of the wind system. More such control schemes for wind power smoothing by regulating the power output of additional energy storage devices are presented in [38] - [44].

4 Design Methodology: Linear Quadratic Optimal Control for Coordinating Regulation from Wind and Storage

Typical power systems practice addresses the frequency regulation problem in the context of a linearization about the operating point, with focus on small disturbance stability of the control design. Best practice in power system planning would follow-up linearized controller design with time domain simulations examining large disturbance, non-linear response in credible disturbance scenarios. We acknowledge that such non-linear simulation tests are not considered in the analysis here, but would constitute an important step in future work to bring the proposed designs towards practice. Hence the small case study here begins from (only) linearized state space models of each of the sub-systems of interest.

4.1 Wind Variation as a Disturbance Signal to Primary Control

In this case study, in keeping with the design methodology of [49], we model periodic variation in wind power using an unforced linear system model, in the terminology of [49], this is the "exosystem." This explicit representation of input disturbances as a "built-in" part of the model facilitates our framework for ensuring actuation stays within limits. It should be noted that the resulting design will only guarantee control within actuation limits for disturbances that fall within this class (admittedly over-idealized). However, this approach does have the attractive feature of allowing one to begin from a spectral analysis of wind speed variation over the time frame of interest (here relatively short – on the order of several seconds), and matching the natural frequencies of the exosystem model to the dominant spectral components observed. The exosystem is then chosen as an unforced linear system with purely imaginary eigenvalues matching the frequencies of interest. The state space representation is given by

$$\dot{w} = Sw$$
 (1)
 $y_{exo} = C_w w$ (2)

where ω are the exosystem states, **S** is the matrix governing the linear dynamics of the states, y_{exo} is the exosystem output, and C_{ω} is the output matrix. As a simple representation of periodic disturbance that allows easy evaluation of performance, here we choose the matrix **S** and appropriate initial conditions on ω such that the exosystem model yields a periodic square wave as the output. In particular, we choose a matrix **S** of dimension 10×10, given by:



where, ω_s is the fundamental frequency of the periodic square wave. Here **S** has along its diagonal 2×2 blocks of skew-symmetric matrices with odd harmonics of ω_s forming the entries on the anti-diagonal. All the other entries of **S** are zero. This choice of **S** results in purely imaginary eigenvalues of the exosystem, the eigenvalues being ±jn ω_s , n = 1, 3, ..., 9. For the specific initial conditions of

$$w_0 = \begin{bmatrix} 0 & 1 & 0 & 1 & \cdots & 0 & 1 \end{bmatrix}^T$$
(4)

direct calculation confirms that $\omega(t)$ trajectories will contain sinusoids at fundamental frequency ω_s and its odd harmonics to order 9. The output matrix C_{ω} is chosen as

$$C_w = \begin{bmatrix} 1 & 0 & \frac{1}{3} & 0 & \cdots & \frac{1}{9} & 0 \end{bmatrix}.$$
 (5)

The resulting output y_{exo} is then simply the truncated Fourier series representation of a periodic square wave, to order 9. While clearly oversimplified relative to meteorologically-based stochastic wind models, this general construction allows one to chose among possible state matrices S, output matrices C_{ω} and exosystem initial states ω_0 to set both the spectral content and the magnitude of the wind power variations represented. This exosystem model thus plays an important role, as it determines the class of disturbance against which the controller must regulate.

4.2 WECC Wind Turbine Generator System Model

The wind turbine generator system is modeled using an industry-standard dynamic model. The representation used is known as the Type-3 Wind Turbine Generator (WTG) Western Electricity Coordinating Council (WECC) generic model, described in detail in [45]. One of the key features of this model is the way in which the wind turbine mechanical behavior is represented. Two coupled rotating masses represent the mechanical behavior of the turbine-generator system. Hence, torsional stress on the coupling between the two rotating masses can be considered. The equations governing this wind turbine model are given by

$$2H_t \Delta \dot{\omega}_t = T_{mech} - K \delta_{tg} - D_{shaft} \Delta \omega_{tg}$$
(6)
$$2H_g \Delta \dot{\omega}_g = -T_{elec} + K \delta_{tg} + D_{shaft} \Delta \omega_{tg}.$$
(7)

Where, H_t and H_g are the turbine and generator inertia constants respectively, ω_t , ω_g are the turbine and generator rotational speeds respectively, T_{mech} is the turbine side torque, T_{elec} is the generator side torque⁴, ω_{tg} is the difference in the turbine and generator rotational speeds, δ_{tg} is the difference in the turbine and generator angles respectively, Kis the shaft stiffness, and D_{shaft} is the shaft damping constant. It is important to note that all quantities in these equations are expressed as per unit (p.u.) normalized values. A good indicator of the torsional stress on the drivetrain shaft is the difference in the turbine and rotor torques, ($T_{mech} - T_{elec}$). Adding (6) and (7), one obtains

$$2H_t \Delta \dot{\omega}_t + 2H_g \Delta \dot{\omega}_g = (T_{mech} - T_{elec}). \tag{8}$$

the time derivatives of ω_t and ω_g can be written as linear combination of the states of the overall system, which includes the power system, the storage devices, and the WTG systems. Thus, the torque difference can be written as a linear function of the system states, and, with appropriate linear transformation, one can obtain a state representation that explicitly includes the torque difference as a component. While not strictly necessary for the development to follow, isolating the torque difference as a component of the state vector makes it straightforward to formulate a control design objective function that well captures the practical goal of minimizing drive train stress.

4.3 Supplemental Primary Control: Model of Power Delivery from Battery Storage

Battery energy storage systems with power electronic grid coupling can have very high bandwidth in their linearized transfer characteristic describing commanded-to-griddelivered electric power; simply put, battery control action is fast relative to the other control time constants of interest. This has the potential to complement the low bandwidth inherent in the mechanical action of wind turbine blade pitch control. However, from the standpoint of grid applications, many practically sized battery systems are very limited in their energy and maximum power. In the control philosophy of this work, batteries are a class of actuator with narrow saturation limits on their available control action, but broad bandwidth. Work in [46] develops linearized models for lithium-ion battery terminal behavior, and shows that this behavior may be represented by a simple circuit composed only of linear capacitors and resistances. When examined in the frequency domain, these models yield Bode plots with a high-pass filter characteristic [47], confirming our premise regarding the qualitative frequency domain behavior of a battery. The high pass nature of the commanded-to-achieved power also confirms the

⁴ Readers will note that unlike the synchronous machine swing equation, here torque appears on the right hand side of the rotational acceleration equation. It is not appropriate to substitute electrical power for torque, because the induction machine's speed cannot be well approximated as nearly constant.

inherent energy limitation of batteries: they cannot provide a steady-state power output all the way down to dc^5 . Hence, the transfer function characterizing commanded-to-delivered power for a grid battery storage "actuator" is here represented with a fourth order high-pass Butterworth filter.

4.3.1 Model of Wide Area Electromechanical Dynamics for Control Design

The state space formulation of the power system model representing wide area electrodynamics is assembled as follows. The electromechanical behavior of a traditional synchronous generator can be captured by standard swing equation models [48]. The frequency ω and angle δ are related by definition

$$\Delta \dot{\delta} = \Delta \omega \tag{9}$$

The equation governing the generator dynamics is given by

$$M\Delta\dot{\omega} = \Delta P_m - \Delta P_e - D\Delta\omega \tag{10}$$

where M is the rotational inertia of the generator, D is the damping constant, P_m is the mechanical shaft power input to the generator, P_e is electrical power output of the generator. ΔP_m can be assumed to be zero, as in this work we are focusing on regulating the frequency due to wind power variations and are not considering changes at the input of a synchronous generator. ΔP_e is the incremental power absorbed by the network at the generator terminal buses.

The state equations governing the various sub-systems (synchronous generators, wind generators and energy storage devices) can be written together with the network power balance equations in the form

$$\Delta \dot{x}_{sys} = A_{sys} \Delta x_{sys} + B_{grid} \Delta y_{grid} + B_{sys} \Delta u_{sys} + E_w \Delta w$$

$$0 = C_{grid} \Delta x_{sys} + D_{grid} \Delta y_{grid}$$
(11)
(12)

where x_{sys} are the overall system dynamic states, y_{grid} are the algebraic variables of the power flow, and u_{sys} are the inputs (battery inputs). The i_{th} row of the matrix E_{ω} corresponding to the wind generator *i* is the same as the matrix C_{ω} chosen in the wind power variation model described earlier. The remaining rows of E_{ω} are set to zero, so that the periodic square wave disturbance input appears only in the input channels associated with the wind generators. The algebraic variables are the standard power flow variables of bus voltage magnitude and phase angle at the respective buses in the network.

⁵ Here we use a lower case "dc" notation to indicate a zero frequency control signal, relevant to the transfer function of a control block or actuator. This is distinct from the previously discussed direct current (DC), non-sinusoidal voltages and currents produced by a photovoltaic panel. The upper case "DC" notation will be reserved for higher-power, direct current quantities in the grid, lower case "dc" for zero-frequency control signals in a Bode plot description.

Equation (12) is a set of algebraic equations that represents the power flow Jacobian relation of the network. For a linearization about the operating point, the Jacobian relates various bus powers and the bus voltages according to a linear set of equations. The number of these equations must match the number of algebraic variables. Thus, barring degenerate operating conditions that yield a singular Jacobian, the algebraic variables can be solved in terms of the dynamic variables using (12), and substituted in (11) to form a standard state equation.

4.3.2 Overall Optimal Control Design for Case Study System

In this section, we briefly review a linear quadratic regulator based design methodology as described in the research monograph [49], which is explicitly developed for applications in which the control action of interest is predominantly linear in its normal range, but subject to hard saturation limits. While it is certainly not the objective of the broad analysis task to limit consideration to a single control design methodology, it is our premise that methodologies that explicitly treat hard saturation limits become very important in the context of high penetration renewables. When many devices with widely varying power output capabilities contribute to active power control on the grid (e.g., wind turbines, photovoltaic panels, storage devices, responsive load) optimal utilization of their capabilities must explicitly respect these limits. First and foremost, these limits will be the relative narrow ranges (relative to overall grid needs) over which any one device can vary its power output. Other state dependent limits of interest will likely include ramp rates (limits on time derivative of power output) and energy charge/discharge limits on storage (limits on time-integral of power). The presentation below describes a particular approach to adapting this LQ-based design method, to exploit the saturation-bandwidth characteristics relevant to the case study scenario of wind turbine pitch control supplemented by battery storage. We then describe a distributed observer-based control scheme utilizing a one local and one remote PMU measurement at each location, thereby taking advantage of advanced measurements while not making unrealistic demands on the number of long-distance communication links required by a given controller.

4.3.3 Control Design with Input Saturation

An optimal control design method for linear systems subject to input saturation has been presented in [49]. In the abstract control design setting, the objective is output regulation against disturbances characterized by an exosystem, where the exosystem is explicitly constructed as part of the overall model. This framework is particularly well suited to the frequency regulation problem in the power systems context, and allows treatment of operational limits that are critical to the successful incorporation of new grid technologies such as wind generation and distributed energy storage technologies.

The optimal control method, called the low gain design method, is based on a linear quadratic regulator problem. Consider a standard linear state space description for the small signal behavior of the system of interest:

$$\dot{x} = Ax + B\sigma(u) + E_w w \tag{13}$$

$$\dot{w} = Sw \tag{14}$$

$$y = Cx \tag{15}$$

Equation (13) describes the plant with state $x \in \mathbb{R}^n$, and control input $u \in \mathbb{R}^m$, subject to the effect of an exogenous disturbance represented by $E_{\omega}\omega$, where $\omega \in \mathbb{R}^s$ is the state of the exosystem. Equation (14) describes the state space realization of the autonomous exosystem, as described in the previous section. The output is $y \in \mathbb{R}^p$, and σ is a normalized vector-valued saturation function indicating the saturation limits on the input.

Conditions for solvability of the output regulation problem include:

(i) All the eigenvalues of A must lie in the closed left-half plane, and the pair (A, B) must be stabilizable,

(ii) there must exist matrices Π and Γ such that they solve the regulator equation

$$\frac{\Pi S = A\Pi + B\Gamma + E_w}{0 = C\Pi}$$
(16)
(17)

(iii) there must exist a $\delta > 0$ and a time $T \ge 0$ such that $\| \Gamma \boldsymbol{\omega} \|_{\infty,T} \le 1 - \delta$ for any allowable initial condition on the exosystem (i.e., the peak magnitude of any component of $\Gamma \boldsymbol{\omega}$ must be bounded strictly less than one over the interval [0, T]).

For the exosystem employed in this work, the magnitude of the disturbance signal is controlled by the size of its initial condition set. Hence, an intuitive measure of the quality of the control design here can be judged as follows: how large a disturbance magnitude can the system regulate, without exceeding the saturation limits on the actuators?

The desired matrix is then obtained via solution of the Algebraic Riccati Equation (ARE)

$$P_{\epsilon}A + A^T P_{\epsilon} - P_{\epsilon}BB^T P_{\epsilon} + Q_{\epsilon} = 0$$
(18)

where, Q_{ε} : (0, 1] $\rightarrow \mathsf{R}^{\mathsf{nxn}}$ is a continuously differentiable, matrix-valued function such that $Q_{\varepsilon} > 0$, $\partial Q_{\varepsilon} / \partial \varepsilon > 0$ for any $\varepsilon \in (0, 1]$, and $\lim_{\varepsilon \to 0} Q_{\varepsilon} = 0$.

The solution of (18) is a unique positive definite P_{ε} that is continuously differentiable with respect to ε , is monotonically increasing with ε , and approaches the zero matrix as ε approaches zero, i.e., $\lim_{\varepsilon \to 0} P_{\varepsilon} = 0$. The state feedback gain matrix F_{ε} is then given by

$$F_{\epsilon} = -B^T P_{\epsilon} \tag{19}$$

where, in the terminology of [49], ε is the low gain parameter. Feedback using F_{ε} yields an asymptotically stable undisturbed system for any $\varepsilon \in (0, 1]$. The feedback control law is given by

$$u = F_{\epsilon}x + [\Gamma - F_{\epsilon}\Pi]w \tag{20}$$

For a system subject to input amplitude saturation, this design, with an appropriate choice of ε , results in exact output regulation with the system operating in the linear regions of the saturation elements, under the previously stated solvability conditions. For the range of power system application examples examined by the authors, these solvability conditions prove easily satisfied.

4.4 Centralized Control Design as Benchmark

We tailor the low gain design method to enhance controller utilization and regulation performance with actuators having complementary saturation-bandwidth characteristics. This is done by partitioning the Q_{ε} matrix according to the characteristics of the input channels. To do so, the system is first transformed into its modal co-ordinates.

Typically in the development of [49], Q_{ε} is chosen as ε multiplying an identity matrix. But here, to exploit the complementary nature of saturation-bandwidth limits, we partition the Q_{ε} matrix parameterized in two different ε values. The influence of each of the input channels on the states can be quantified by looking at the modal degrees of controllability. In particular, for each input channel, i, and each mode of the system, k, define the scalar $m_{i,k}$ given by

$$m_{i,k} = |\mathbf{w}_k^T \mathbf{b}_i|. \tag{21}$$

Here, \mathbf{w}_k is the normalized left eigenvector of A corresponding to the mode k (normalize to $||\mathbf{w}_k|| = 1$), and \mathbf{b}_i is the *i*th column of B. This provides a way to rank pairs of modes that are most controllable through a particular input channel. Once this is known, corresponding 2x2 diagonal blocks of the Q_{ε} matrix can be weighted with appropriate ε . For the high bandwidth, low saturation limit input channels, the resulting diagonal blocks of Q_{ε} matrix are weighted with the larger ε value; conversely, lower bandwidth, higher saturation limit channels are weighted by smaller ε value. This simple modal-based tailoring of the low gain design method complements the characteristics of the actuators.

4.5 Distributed Control Design for Practical Implementation

In a large-scale power system spanning distances of several 100 miles or more, a realtime full state feedback control scheme that communicates measurement controllers and system states to every controller is clearly not practical. While we argue that the proliferation of PMU measurements suggest their broader exploitation for control, one must recognize that highly secure, low-latency communication of the type needed for feedback remains expensive in the power systems context. Therefore, here we propose a distributed observer-based scheme using minimal communication, in which each device's input command is generated by a local controller. The design choice applied here severely restricted (but did not completely eliminate) communication. Each local controller consists of an observer-fed state feedback that is allowed to use any local measurements, and at most one remote PMU measurement.

The observer is allowed to use any local measurement signal, but is restricted to a very small number of remote measurement signals (again, only one in the examples to follow). Phasor measurement unit (PMU) signals can be used as the measurement signals to be fed to the observer. PMUs provide accurate time-stamped measurements at high rates, typical rates being 30 cycles per second. The class of measurement signals we choose for the state observer process are the synchronous generator bus frequencies and angles.

A key aspect of the proposed distributed control scheme is a modal-focused approach. It is typical in power systems practice that a modest number of poorly damped, oscillatory electromechanical modes are of greatest concern, and their poor damping can undermine good frequency regulation performance. A controller that improves damping of critical modes can improve both overall electromechanical stability and regulation performance. Hence, design focuses on this subspace of critical modes.

The controller design consists of two components: observer design and state feedback design. For the feedback design, the low gain design method described in the previous subsection is adopted. The partitioning of the Q matrix is done by looking at the most controllable modes among the subset of critical modes for a given actuator. This feedback control is fed by the local observer that dynamically estimates system states based on a PMU measurement signals set. An observer design is adopted here. In this approach, the set of measurement signals that lead to good observability across the set of critical modes is chosen as the signal set to be fed to the observer input. The equation governing the observer dynamics is given by

$$\Delta \hat{\overline{x}}_{comp}^{i} = \overline{A}_{comp} \Delta \widehat{x}_{comp}^{i} + \overline{b}_{comp}^{i} \Delta \overline{u}_{i} + \overline{E}_{w} \Delta w + L^{i} (\Delta \overline{y}^{i} - \overline{C}_{comp}^{i} \Delta \widehat{x}_{comp}^{i}).$$
(22)

Where, *i* denotes the observer/actuator location index, x_{comp} denotes the states estimated by the observer, A_{comp} denotes the state matrix of the composite system (plant and actuators together), b_{comp} denotes the in column of the input matrix B_{comp} , u_i denotes the input to be fed to the actuator, L_i denotes the observer gain matrix, C_{comp} denotes the output matrix. The matrix L_i is designed according to the method described in [18]. The dynamics of the system are governed by

$$\Delta \dot{\overline{x}}_{comp} = \overline{A}_{comp} \Delta \overline{x}_{comp} + \sum_{i=1}^{k} (\overline{b}_{comp}^{i} \Delta \overline{u}_{i}) + \overline{E}_{w} \Delta w.$$
(23)

Here, k denotes the number of actuators in the system, x_{comp} denotes the states of the composite system. The control law u_i is given by

$$\Delta \overline{u}_i = F^i_{\epsilon} \Delta \widehat{x}^i_{comp} + (\Gamma^i - F^i_{\epsilon} \Pi^i) \Delta w$$
 (24)

where, F_{ε}^{i} , Γ^{i} and Π^{i} are the state feedback, solution of the regulator equations respectively for a particular location, indexed as location i. These matrices are different for different locations, as they depend on the given location's b_{i} , (i.e., the particular input channel characteristics at that location) and $C_{i,comp}$. (i.e., the particular outputs measured at that location).

4.6 Reduced Order Controller Synthesis

The observer-based distributed control scheme described above is practically feasible, as it involves the use of local controllers feeding the local actuators, and the observer uses a small subset of available measurement signals, thereby reducing the costs associated with communicating PMU signals. However, for a large scale system such as the power grid, a scheme designed to estimate the full order state will be computationally challenging. So, we propose here an order reduction technique to form controllers of much smaller dimension.

We seek a reduced order controller (observer and state feedback together) by looking at the transfer characteristics of the controller block, which has the exosystem states and measurement signals as the input set, and the control command to be fed to the local actuator as the output. Since it is only the observer block that has dynamics (the state feedback block implements static gain matrices, F_{ε}^{i} , Γ^{i} and Π^{i}), a reduced order controller with order equal to the dimension of the subspace on which the design has been performed should lead to performance close to the full order controller. We seek the construction of the reduced order controller by first forming the balanced realization system of the full order controller. Then, we choose the most "important" modes (equal in number to the dimension of the design subspace) in this transformed system. Once these modes are identified, the reduced order controller can be formed easily by eliminating the unwanted states. The performance of this distributed optimal control method, in the context of this test system, is evaluated with respect to both the systemwide control objective (stable frequency regulation) and a local control objective (minimizing stress in the wind turbine model's drivetrain).

5 Case Study: Multi-Objective Evaluation of Optimal Control Performance

In this section, we demonstrate the control design methods proposed in the previous section on a test power system. We consider the standard IEEE 14 bus system to demonstrate the control methods. The resulting frequency regulation, and reduction in torsional stress on the drivetrain are presented to demonstrate the effectiveness of the control methods. The IEEE 14 bus system consists of 5 synchronous generators and 9 loads. We replace two of the synchronous generators with wind generators. The wind power variation at the input of each of the wind systems is modeled using the exosystem model presented earlier. The variations in wind power get reflected on to the system as variations in frequency at the synchronous generator buses.

To monitor a single signal representative of system frequency, we look at the weighted of the frequencies at each of the traditional generator locations (each frequency weighted by the respective generator inertia). The resulting plot of frequency without any supplemental control from a storage device is shown in Fig. 1. As can be seen from the figure, the frequency deviations do not go down to zero and have amplitude of about 0.9 Hz varying about the nominal 60 Hz value. The resulting turbine and rotor torque difference for one of the wind generators is shown in Fig. 2. The plot of torque difference for the other wind generator system is almost identical to this plot, and hence is not shown here.

Next, we demonstrate the distributed observer-based control method on this test system. We have one observer-based controller feeding a battery at a traditional synchronous generator location. Since the actuator associated with the wind generation system, the blade pitch controller, is already part of the WECC WTG model, we avoid adding any external feedback signal to the wind system. The objective of the controller is to regulate the frequency, and reduce the difference in the turbine torque and rotor torque. The turbine and rotor torque difference is constructed as an explicit state in the control design, as described in the previous section. The local generator frequency and angle measurements, and one remote measurement in the form of the other generator frequency are used by the observer to form the state estimates.



Fig. 1. Time Plot of Frequency variation no control case – it displays periodic variation due to the periodic input disturbance.



Fig. 2. Drivetrain stress indicated by torque difference $(T_{mech} - T_{elec})$, no control case.



Fig. 3. Frequency behavior with feedback design 1 – control objective not including torque difference.

The control design is performed on a low dimensional subspace associated with the set of lightly damped oscillatory modes in the system. We first demonstrate the control scheme on the system model with the objective of frequency regulation, but without having the turbine and rotor torque difference as an explicit state. The resulting plot of frequency is shown in Fig. 3. Clearly, this controller is able to regulate the frequency to its nominal value (within acceptable band of frequency regulation). The resulting plot of turbine and rotor torque difference for the same wind generator as considered in the case without the control is shown in Fig. 4. Comparing this with the torque difference for the case without any control in Fig. 2, we can see that this controller is not successful in reducing the torsional stress on the wind system drivetrain.

Next, for the same system as considered above, we demonstrate the distributed control scheme, with an addition that the turbine and rotor torque difference is constructed as an explicit state in the control design. The resulting plot of frequency is shown in Fig. 5. The controller is thus able to regulate the frequency to its nominal 60 Hz value. The resulting turbine and rotor torque difference is shown in Fig. 6. Comparing this with the torque difference without any control in Fig. 2, it is clear that the controller is able to reduce the drivetrain stress significantly. Also, it performs better than the control design in which no torque difference was considered in the design objective (Fig. 4). Thus, this control scheme is not only able to regulate the frequency, but also reduce the stress on the drivetrain significantly.



Fig. 4. Torque difference $(T_{mech} - T_{elec})$ with feedback design 1 – control objective not including torque difference.



Fig. 5. Frequency behavior with feedback design 2 – control objective does include torque difference.



Fig. 6. Torque difference $(T_{mech} - T_{elec})$ behavior with feedback design 2 – control objective does include torque difference.

We also monitor the effect of this control on the turbine side torque, T_{mech} . The turbine side torque for the case with- out any control and for the case with the control (considering reduction in turbine and rotor torque difference as part of the objective) is shown in Figs. 7 and 8 respectively. Comparing these two plots, we can see that the controller is able to reduce the peak turbine torque by almost half. The resulting plot of the output power of the battery is shown in Fig. 9. To get an estimate of the battery output power, we look at the actual value. The system MVA base for this example is 100 MVA. Thus, a battery output power value of $2x10^{-3}$ p.u. corresponds to 200 KW. So, for a battery installation of 2 MW (typical of test installations today), the output power variation used for frequency regulation here would represent 10 percent of the installed capacity.



Fig. 7. T_{mech} behavior without control.



Fig. 8. T_{mech} with feedback design 2.

Finally, we demonstrate a reduced order controller as proposed in the previous section. Four pairs of critical modes (poorly damped oscillatory modes) are chosen for the design of the controller. The reduced order controller is also chosen to have order eight. The resulting plot of frequency is shown in Fig. 10. Here, the frequency is plotted for both the full order controller and the reduced order controller. The figure displays insignificant difference between the two, i.e., the reduced order controller performs as well as the full order controller. The resulting turbine and rotor torque difference for both the full order and the reduced order controllers is shown in Fig. 11. Again here, the reduced order controller is able to reduce the drivetrain stress significantly, performing as well as the full order controller (imperceptibly different in the resolution of the plot).

This case study has considered a distributed design for control of power using an industry-standard wind powered electric generation model, supplemented by a modest amount of controllable storage. The optimal control design is able addresses dual goals: the system-wide objective of contributing to grid frequency regulation, and the local, "equipment-centric" goal of minimizing mechanical stress in the wind turbines. For a two-rotating-mass representation of the wind turbines, we consider a contribution to objective that penalizes torque difference between the two masses. An LQ-based design that includes this term in its objective is shown to simultaneously improve system-wide frequency regulation and reduce wind turbine drivetrain stress.

The methodology also includes an explicit model for exogenous wind power variations, and adapts the low gain technique of [49] to produce a design guaranteed to maintain actuation within saturation limits. In practical terms, this guarantees that the actuation command stays within the relatively modest power limits (modest on the scale of grid operations) appropriate to battery systems. The remaining elements of the method also tailor it to the electric power application. First, control effort is focused on behavior within a subspace associated with a small number of lightly damped electromechanical modes of interest. This greatly reduces the dimension of state observers that must be implemented, with each local controller having an observer that estimates state behavior only for the modes "needing" control. With this reduced-dimension estimation problem comes a reduction in the number of measurements needed to yield adequate observability. In the power systems context, use of geographically remote measurements is sometimes necessary to observe so-called "inter-area" modes, yet imposes high cost associated with long-distance, low-latency communication meeting security standards for critical infrastructure. Hence our local controller employs the minimum number of such remote measurements. In the test case examined, with an overall state dimension of 36, at most a single remote measurement proved adequate for good (subspace) observability. In the example case examined, the local observer-based controllers yielded very good overall control performance in the dual objectives of frequency regulation and turbine torsional stress reduction, while maintaining actuation within saturation limits.



Fig. 9. Battery output power with feedback design 2.



Fig. 10. Frequency Regulation Performance of full order vs. reduced order controller (feedback design 2) – behavior is nearly identical up to accuracy of plot.



Fig. 11. Drivetrain Stress Performance of full order vs. reduced order controller (feedback design 2) – behavior is identical up to accuracy of plot.

6 Conclusions and Future Directions

To close, we repeat once again the fundamental premise of this white paper: that for the greatest benefit of high penetration renewables to be realized, one must "open up" the design space of their control systems, and maximally utilize their flexibility inherent in being power electronically coupled resources. The appeal of producing control response characteristics that seek to match those of long successful strategies in traditional synchronous machines, tightly constraining these new classes of equipment to replicate old technologies (as in the currently popular inertial emulation approaches) is apparent. However, such approaches will inevitably limit renewables to less than full contribution to primary and secondary control (e.g., supplemental controls on renewables will never mimic inertia as well as those machines that implement it as an inherent law of their physics). This white paper instead proposes that future control schemes seek to maximally exploit the widely differing control characteristics of the diverse generation and storage technologies that will contribute to the future U.S. power grid. While there are many advanced control design methodologies that could offer such benefits, as a proof of concept this work has presented a case study applying a Linear Quadratic Optimal Control scheme to coordination of wind energy active power control with storage. It is hoped the promising performance reflected there will inspire further research into advanced primary and secondary control schemes to facilitate larger penetrations of renewable generation. Complementing high penetration renewables, the authors believe advanced control and estimation techniques will prove important to facilitate contributions to primary and secondary control from a range of smart grid technologies including storage and responsive load.

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