Primary and Secondary Control for High Penetration Renewables

A Broad Analysis White Paper prepared for the project

“The Future Grid to Enable
Sustainable Energy Systems”

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PSerc Webinar Series

Synopsis

- Argue for new control design philosophy, to allow renewables to more broadly contribute to grid active power & frequency control.
- Move beyond present approaches that focus on making renewables mimic characteristics of traditional turbine/synchronous generator sets.
- Exploit opportunities in improved grid measurement & sensor technologies (i.e, PMUs) to facilitate designs based on optimal control. Tailor to specific (and very different !!) dynamic characteristics of renewables.

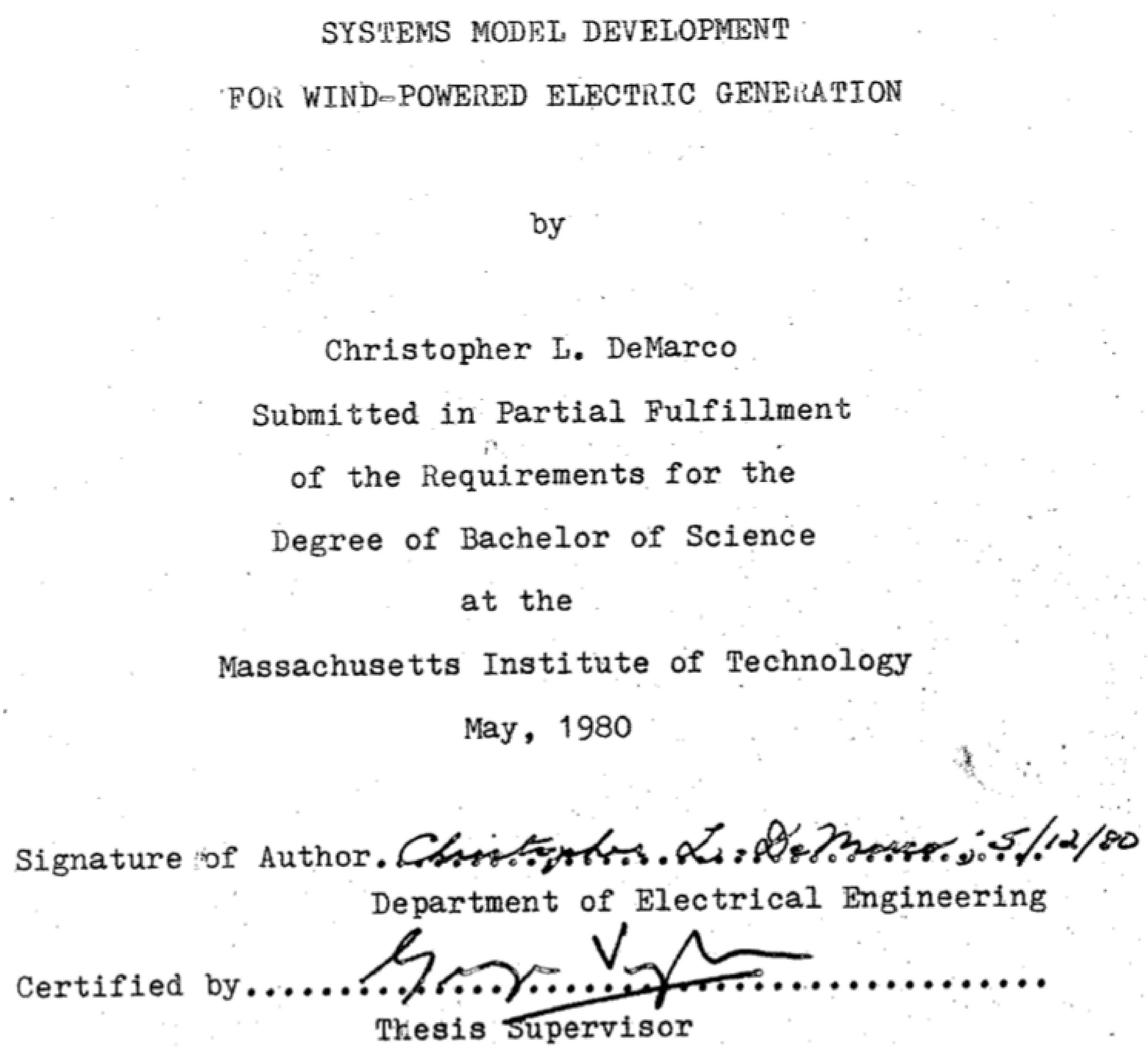
Motivation and Background

- Large scale renewable generation growth suggests potential/need for corresponding growth for its role in grid control;
- Voltage/Var control aspects of renewables already seeing emerging standards;
- Premise here: new challenges and opportunities today lie in control related to active power, frequency, and electromechanical stability.

Motivation and Background

(including indulgence of presenter's own background…)

- In islanded, off-grid applications, coordination of wind MW control w/ synchronous generators has long history.
- Large-scale grid applications may be new, and hardware radically changed, but late 70's early 80's saw much research on active power & frequency control for wind.
- This literature includes a certain 1980 MIT undergraduate thesis, reporting results of arduous summer field work on the Cape Cod island of Cuttyhunk.



SYSTEMS MODEL DEVELOPMENT
FOR WIND-POWERED ELECTRIC GENERATION

by

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Submitted in Partial Fulfillment
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Certified by...
Thesis Supervisor

Cuttyhunk Island
Wind Turbine,
circa 1980. Not
visible in this postcard
photo is a load bank of
thyristor-controlled
resistors.

These provided wide bandwidth active power control, to coordinate w/ primary governors of diesel-driven synchronous generators on island.

Motivation and Background

In context of active power/frequency regulation, control broadly classified in two categories:

"Primary Control" predominantly local, fast time scale automatic feedback on individual units. Design may be coordinated, action is individual.

"Secondary Control" is wider-area action, quasi-static, on slower time scale. Control is focused on coordination across many units.

What Distinguishes Traditional Generation Sources?

- Consider traditional contributors to active power & frequency. Almost all synchronous generators, driven by turbines with valve-controlled gas or fluid flow (water, steam, natural gas).

  Key features from control dynamics perspective:

  (i) turbine's input mechanical shaft power is controllable (range & speed of valving distinguish different classes);

  (ii) the inherent physics of synchronous generator forces exact coupling of mechanical rotational speed & terminal electrical frequency.

What Distinguishes Renewables?

- Contrast traditional sources w/ two classes of renewables, wind and photovoltaic. First, “input” power is harder (but certainly not impossible!) to control.
- Consider wind, at a given wind speed. Change mechanical power “in” by changing aerodynamic efficiency of blades: pitch control or speed control.
- Consider photovoltaic panel, at given insolation level. By changing voltage vs. current operating point of the panel, achieve changes insolation-to-electrical output power efficiency.

What Distinguishes Renewables?

- For wind & photovoltaic, no surprise that flexibility for +/– variation of power come at price of moving off peak conversion efficiency point (less energy harvested).

- Second contrast to traditional sources more subtle. For modern wind machines, and all photovoltaics, there is no tight coupling of interface electrical frequency to the speed of a large rotating mass (as is case for synchronous turbine/generator sets).

- Interface behavior of power electronic coupled sources very different –renewables said to "lack natural inertia."

What Distinguishes Renewables?

- Third difference if renewables to become significant contributors to active power control: much larger number of individual units contributing, with much narrower +/– range of controllable MW power output from any individual unit.

- In language of control design, renewables likely to have much narrower saturation limits on their available short term control action. Our premise: this puts greater premium on control methods that explicitly consider these saturation limits in the design process.

Managing Renewable Differences: Today's Strategy

- Disclaimer/apology: presentation here will (perhaps excessively) critique approach in recent research & in wind vendor offerings. However, real goal is to emphasize promise of new approaches.
- With apologies said, the ox to be gored is "inertial emulation" in renewables' control.
- What is is it, and why has it garnered so much attention?

Managing Renewable Differences: Today's Strategy

- Repeat – power electronic coupled renewables said to "lack natural inertia."
- Suggests a strategy. With the flexibility inherent in their power electronic converters, can we operate renewable generators in fashion that mimics the (presumably desirable) inertia of synchronous machines?
- To first approximation, answer is yes. But need to understand exact role inertia plays – some freshman physics, some EE of synchronous machines, some understanding of assumed power systems practice.

Inertial Emulation – Physics

- Freshman Physics –Newton’s Law:

  (net) Force = Mass X Acceleration

  In rotational form relevant to a generator:

  (net) Torque = Inertia X Rotational Acceleration

- Also for rotational systems, recall physics tells us that:

  Power = Torque X Rotational Speed

Inertial Emulation – EE

- By design, a synchronous machine has sinusoidal electrical current & voltage at its terminals, with electrical frequency exactly proportional to rotating speed.

- Suitably normalized, rotational speed equals electrical frequency (and hence acceleration = d{frequency}/dt).

- Also, electromechanical efficiency extremely is high, >95%. Result is that torque associated with magnetic fields produced by machine windings, when multiplied by speed, almost exactly equals electrical power output.

Inertial Emulation – Grid Practice

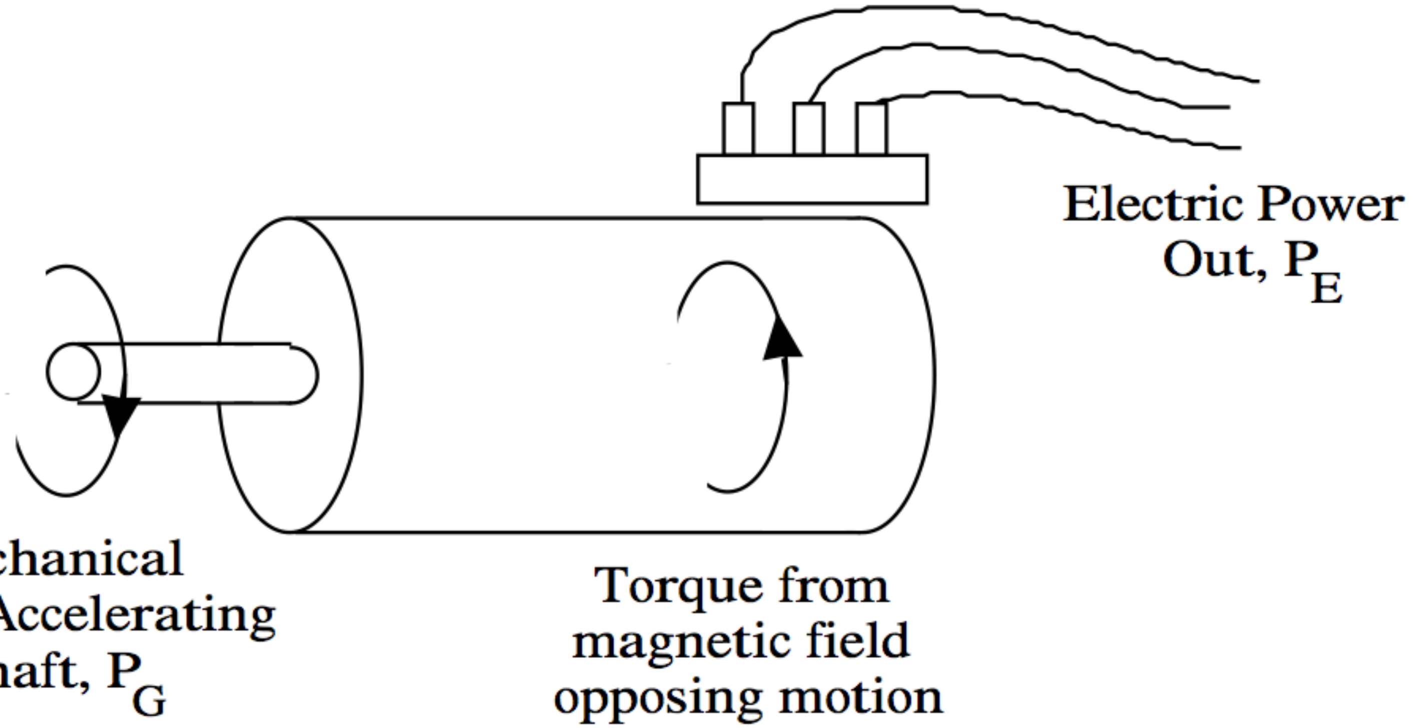
- The U.S. power grid is very good at frequency regulation; VERY rare to see more that ±0.5% variation.

- So, if Power = Torque X Speed, and Speed= Frequency, and Frequency doesn't change by more that ±0.5%…

(again, up to normalization) Torque ≈ Power

Inertial Emulation – Grid Practice

- Back to Newton’s Law, synchronous machine yields:
  (Rotational Inertia)X(d{frequency}/dt)
  = (Mechanical Power “in” from Turbine)
  – (Electrical Power delivered “out” to Network)



Inertial Emulation – Grid Practice

- Viewing Newton's law as a power balance equation, the effect of inertia is another power term.

KEY IDEA IN LITERATURE: To mimic the inertial effect in a non-synchronous, power electronically coupled renewable generator. And looks easy: just need to add a controllable power term, proportional to time derivative of frequency.

Inertial Emulation – Critique

Seems reasonable - so what's the criticism?

Put on the hat of a control system design engineer. Observe that key measurement at any generating unit is its terminal frequency; a key commanded input is the power desired from the unit.

- From this control design perspective, inertial emulation is nothing more than a derivative feedback control!
- Derivative feedback control is not bad, per se, but it is one piece of the simplest, most basic control design idea any 3rd-year undergraduate learns (PID control). OK for simple single-input/single-output systems.

Inertial Emulation – Critique

- For large scale, multi-input/multi-output systems like the power grid, derivative feedback seems, well… "unambitious." It has well-known practical problems, chiefly poor high frequency noise/disturbance immunity.
- In applications for wind energy, inertial emulation needs further filtering to moderate drive train stress.
- So any practical control implemented based on inertial emulation will be far from the underlying ideal, due to bandwidth limits. Strong evidence suggests one could do much better if bandwidth limitation explicitly treated in the control design process.

Vision of Future Control Strategies for Renewables

- From design perspective, renewable generators are control “actuators,” taking commanded power change as an input, achieved electrical power change as an output.

- Previous discussion suggest that they have (at least) two constraints as actuators, that good design should optimize within: (i) bandwidth limits; (ii) saturation limits.

- Moreover, their general transfer characteristics are quite different from traditional synchronous machines. Applying traditional control strategies, while workable, will likely be far from optimal.

Vision of Future Control Strategies for Renewables

- Important enabler: new measurement and sensor technologies, most notably PMU's.

- Traditional primary control of a generator relies on immediately available local measurement only – typically just local frequency.

- If *only* local frequency measurement is available, "tweaking" of traditional control designs (e.g., inertial emulation) may be OK.

- However, if one assumes that even a *very small number of* remote PMU measurements are allowed to be used in control design, door is open to dynamic state observation. With this come significant potential improvements in renewables' control performance.

Vision of Future Control Strategies for Renewables

- With added sensor information to "feed" control, long history of developments in control design offer several families of powerful design methods, any one of which could be effective for enhancing renewables' grid contributions: H-infinity; Convex Optimzation methods/LMIs, and/or Linear Quadratic (LQ) methods.

- As proof of concept, the work here presents a research case study, based largely on the LQ design methodology.

- Primary objective here is not to advocate one method, however.
  Key goal:
  Emphasize promise of new measurement technologies, coupled with optimal control methods, to allow renewables to be larger contributors to grid primary and secondary active power control.

Case Study:A Future Control Strategy for Renewables

- Choice for case study here sought a plausible scenario in which our proposed feedback control could be added to an already validated model for renewable generation. This led us to focus on wind generation, with the WECC Type-3 “generic” model.

- Consistent with earlier observations and engineering common sense, WECC type-3 model shows relatively low bandwidth in the turbine’s controllable power response (i.e., one is not allowed to change the mechanical shaft power too rapidly).

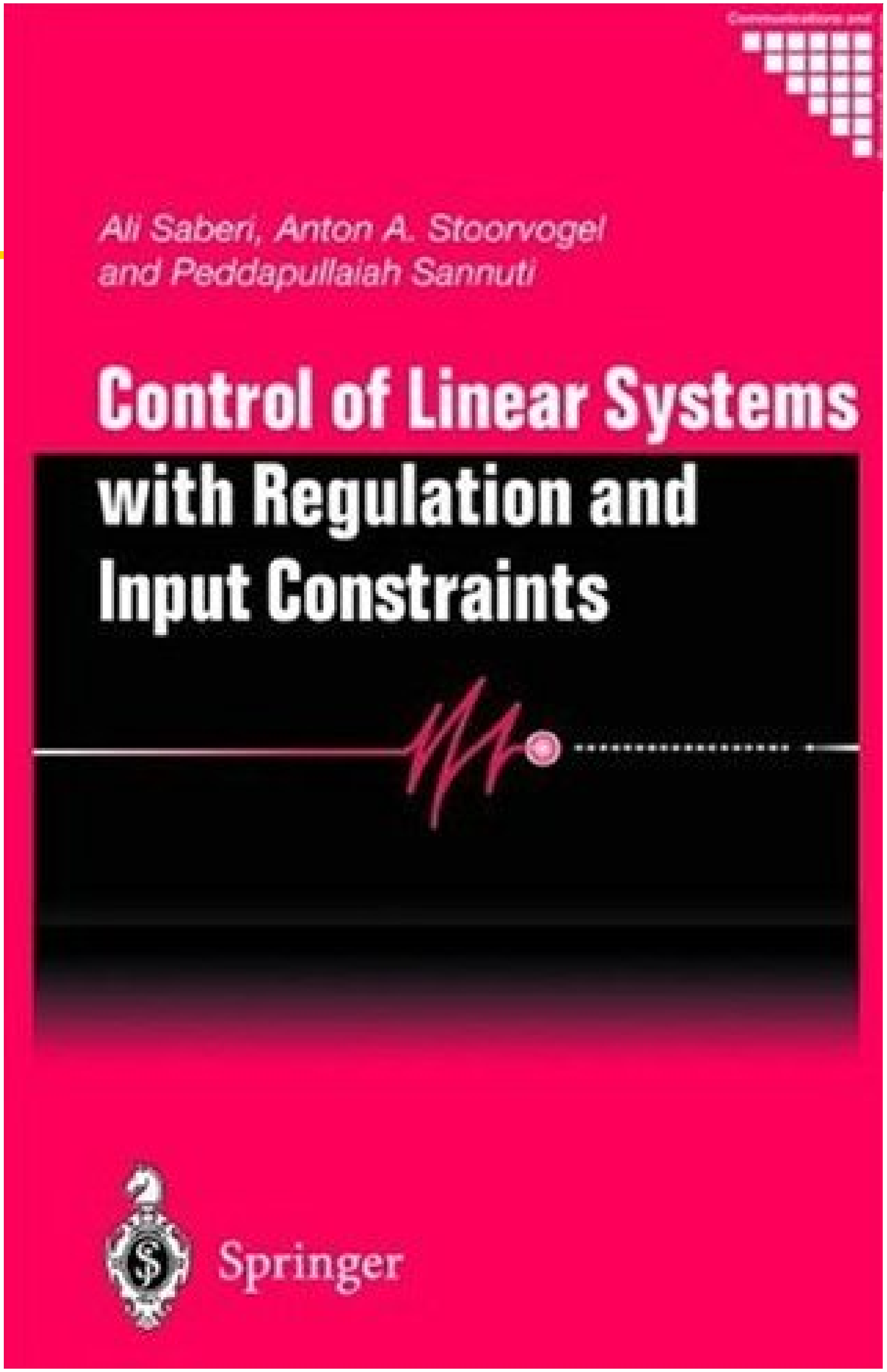
- To complement this, sought a second source of controllable power with broader bandwidth, but smaller MW saturation limits. Experimentally-validated Lithium Ion battery models are found in the literature, so these selected as complementary control source (photovoltaics could also play this smaller/faster MW control role).

Illustrative Design Method & Case

Specific control design method selected for its ability optimize action within specified saturation constraints (e.g., +/– limits on controllable MWs available from wind turbines or batteries).

We chose an LQ-based method developed by Saberi and his co-workers, from research monograph(pictured) published 2000.

Illustrated in context of standard IEEE 14 bus network topology, augmented with WECC “generic” type-3 wind model at two buses.

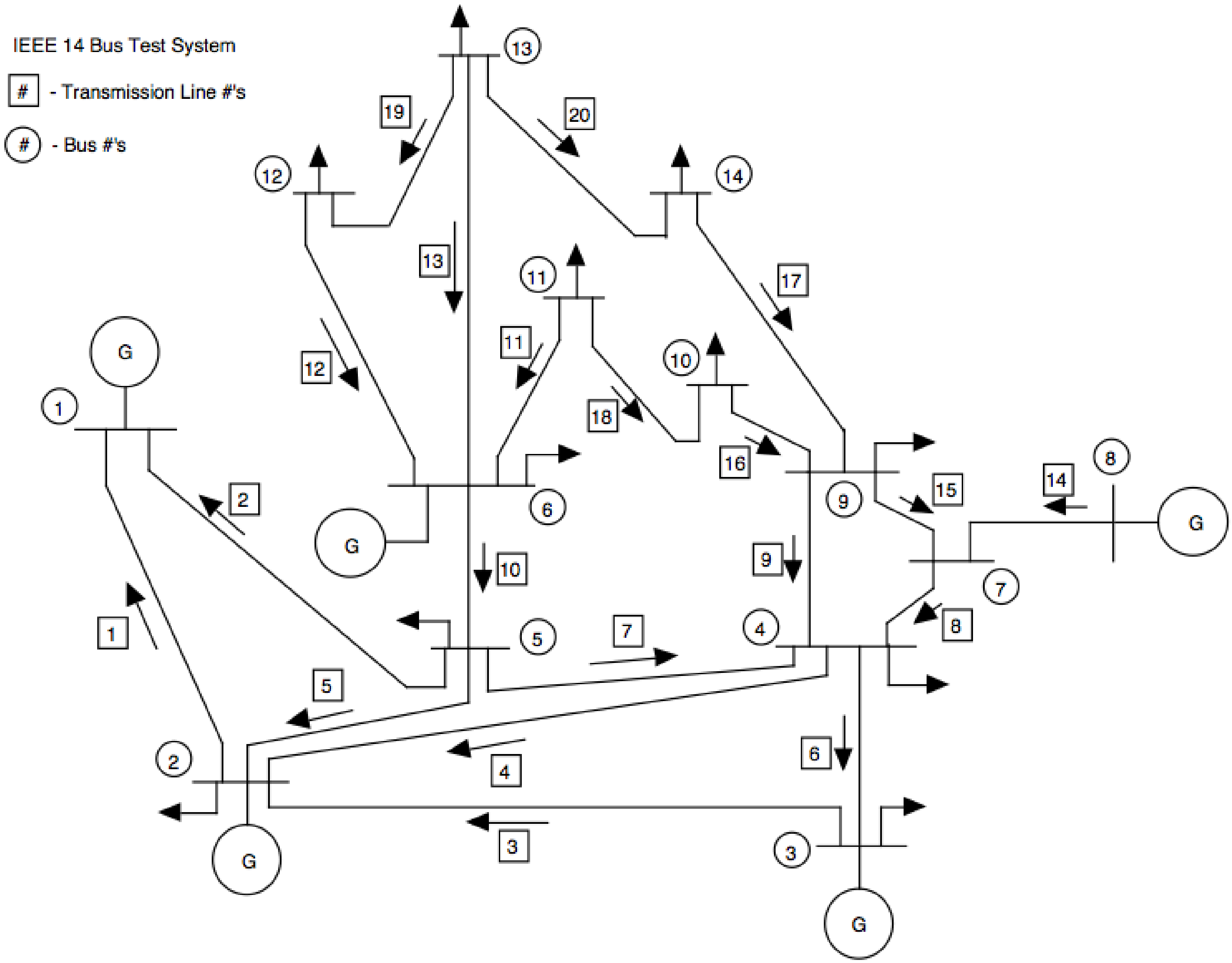


Ali Saberi, Anton A. Stoorvogel
and Peddapullaiah Sannuti

Control of Linear Systems with Regulation and Input Constraints

Springer

Illustrative Design Example



Illustrative Design Example

- This is very preliminary proof of concept – illustrate improved multi-variable performance with optimal control, as compared to behavior with standard WECC type-3 wind turbines and traditional synchronous generator controls alone.

- Admission of unfair contest in this example:
  Our design shows improvement both due to more sophisticated estimation/control algorithm (main point here), **AND** due to our addition of small magnitude, broad bandwidth MW sources to complement the slower control response of wind machines.

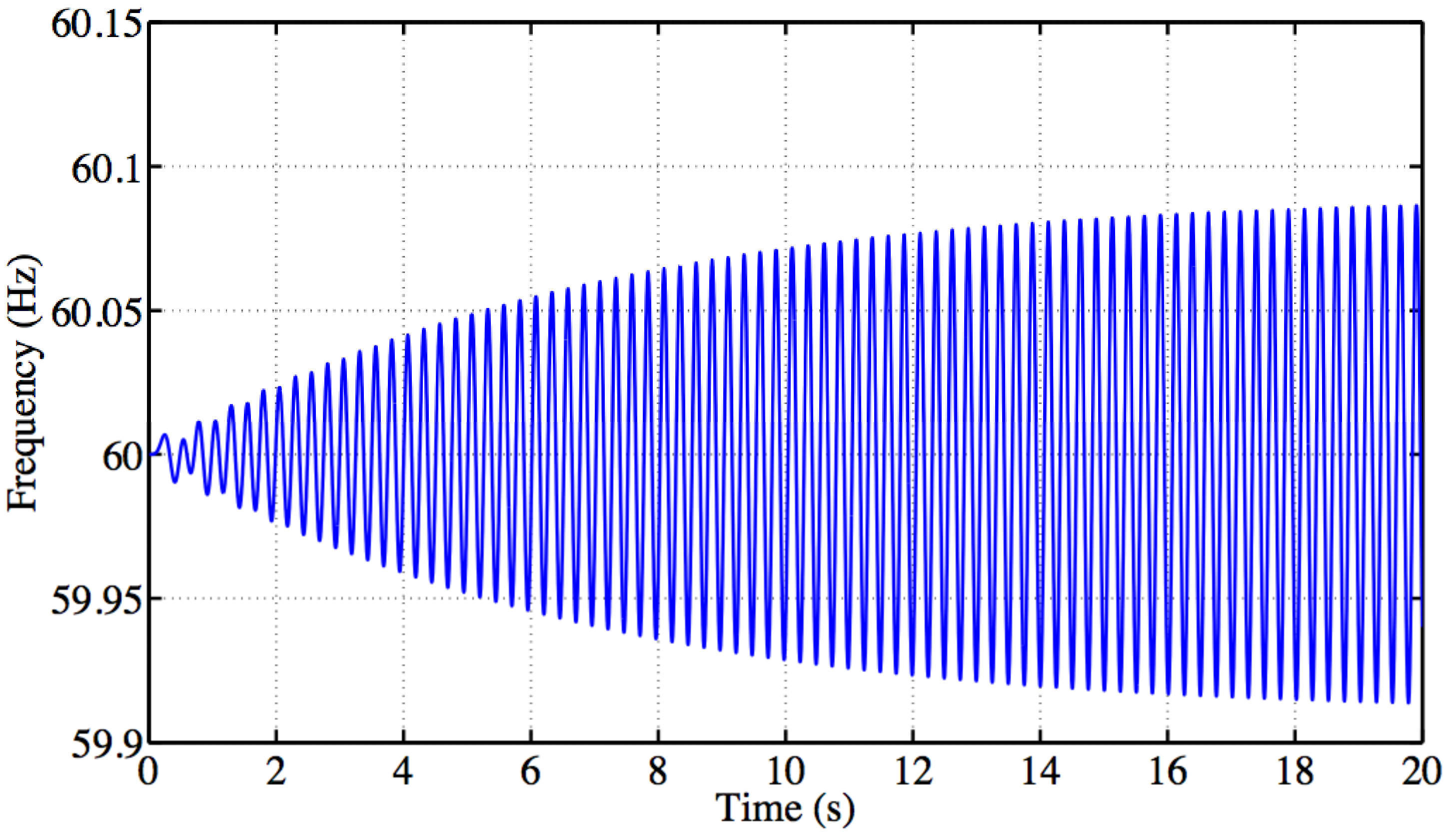
- Here the small MW source is batteries; but could be fast control of PV, or responsive load, or, reaching back to 1980 Cuttyhunk example of introduction, a thyristor-controlled resistive load bank. The design method is agnostic as to source of power; key attributes are its MW response bandwidth and saturation limits.

Illustrative Case Study: Performance Results

- Important to recognize a “trick” in the design method. It adopts an explicit model for disturbances (i.e., fast-time scale variations in MW demand and power output we must regulate against).
- In particular, a component of overall model here is an oscillatory, unforced linear subsystem with natural frequencies selected to approximate spectral content of disturbances of interest.
- With disturbance model “built-in” (as opposed, say, to an external stochastic characterization of disturbances), design method can optimize control action within saturation limits with respect to any ***modeled disturbance***.
- Plots to follow will reflect this periodic nature of assumed disturbances in observed steady state performance, both in the base case and in our improved design.

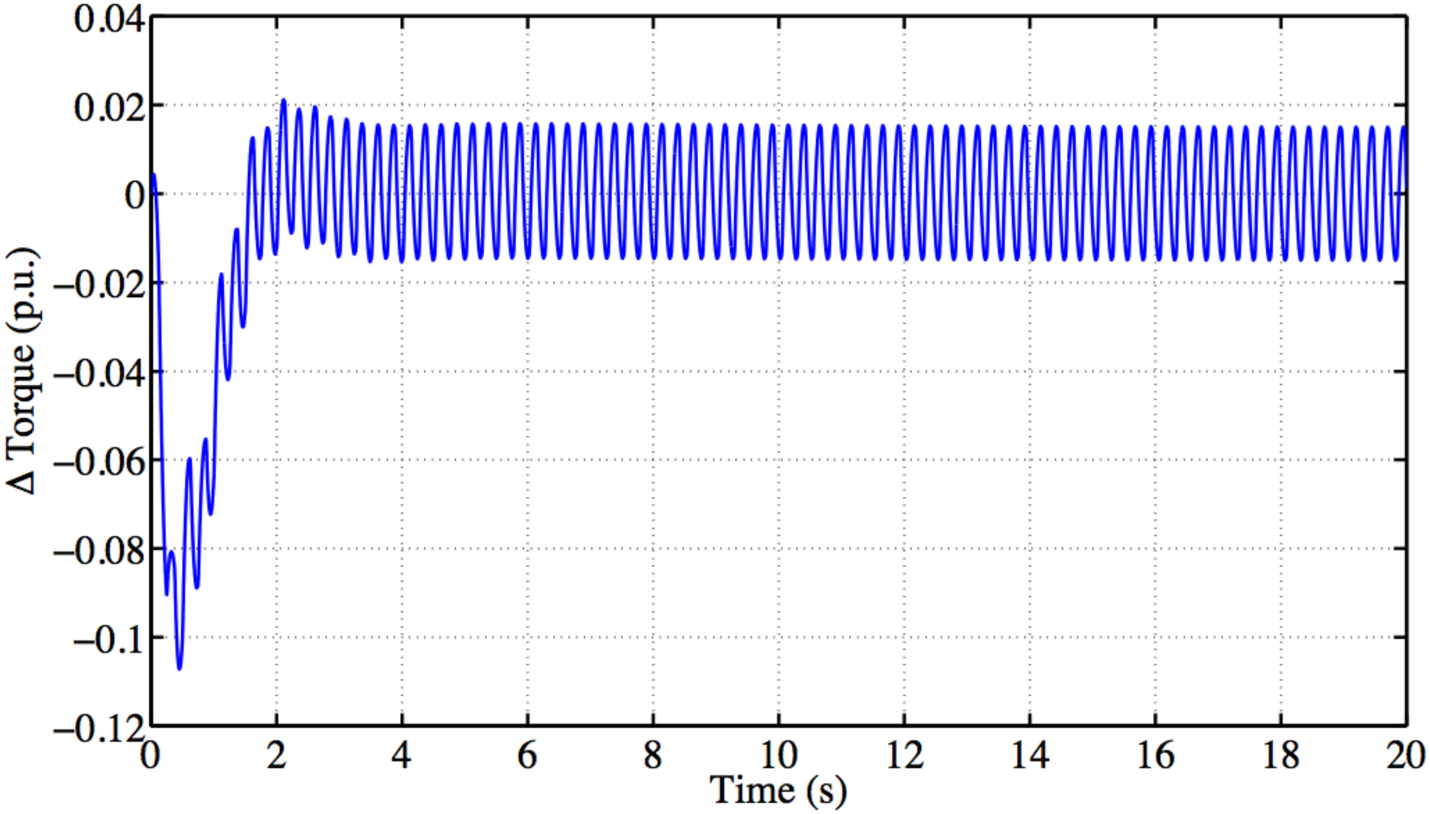
Illustrative Case Study: Base Case Performance Results

- Below: system frequency vs. time with only "standard" WECC type-3 controls, and droop governor control on synchronous machines



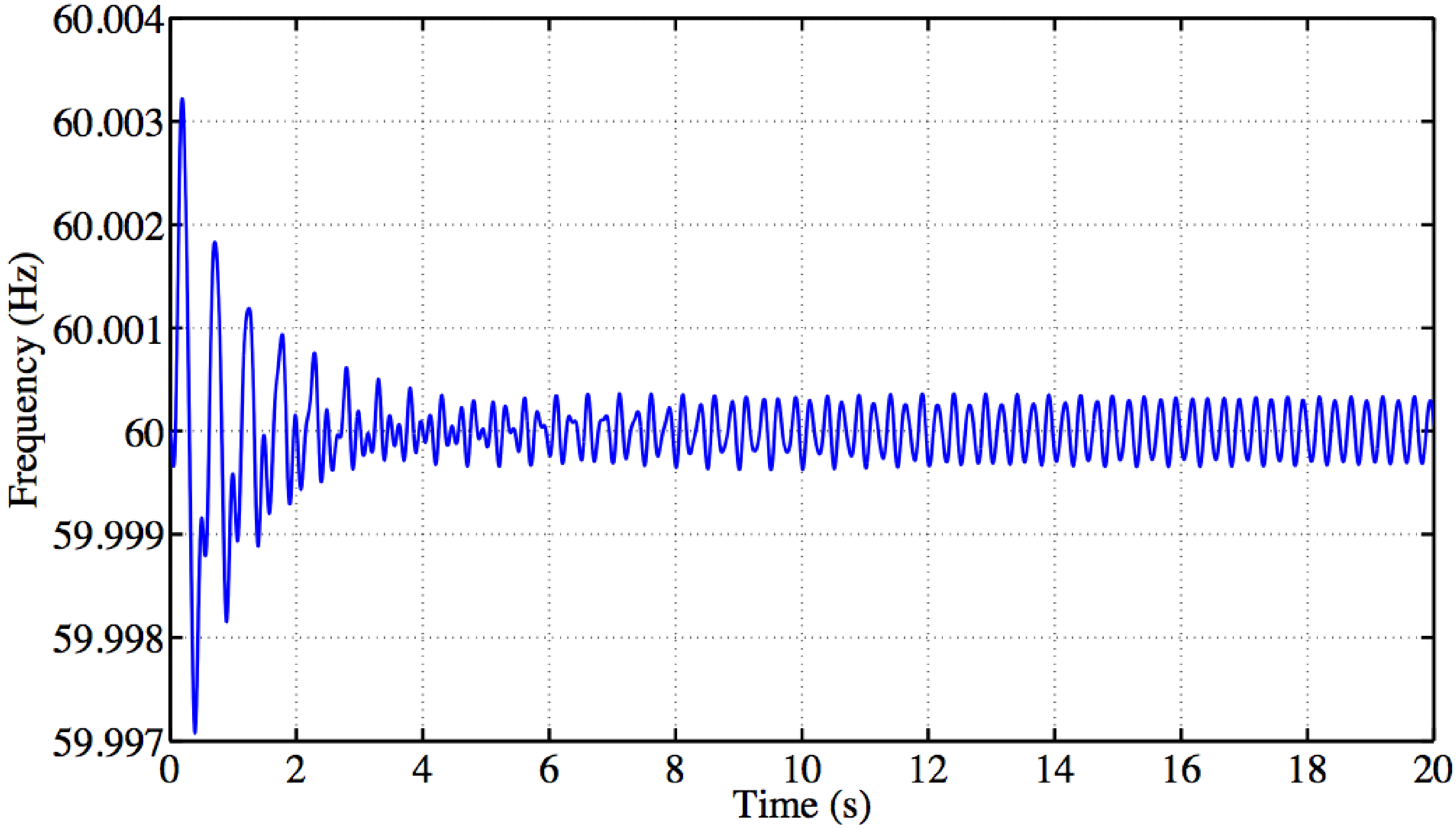
Illustrative Case Study: Base Case Performance Results

- Below: local performance measure on wind machines – torque difference between blade rotating mass and generator rotating mass – indicative of drive-train stress in machine



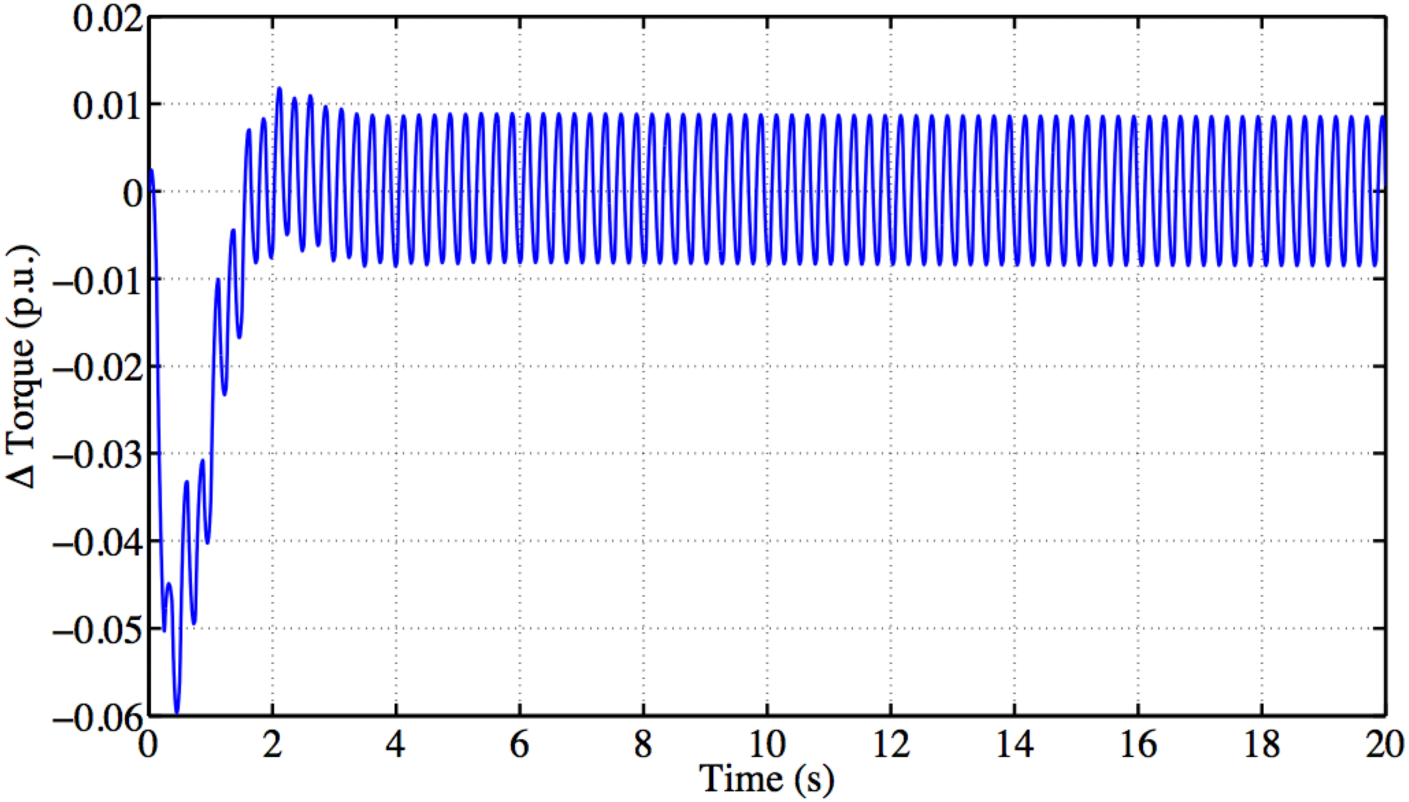
Illustrative Case Study: Optimal Design Performance Results

- Below: system frequency vs. time with optimal control design, including fast control from batteries – ~100x improvement!



Illustrative Case Study: Optimal Design Performance Results

- “Side benefit” in a multivariable optimal design - can simultaneously improve multiple performance measures. Magnitude of torque difference/drive-train stress in machine is also reduced by ~2x.



Illustrative Case Studies: Sources for Added Detail

Brief slides unavoidably gloss over many technical details needed to judge these designs. For added detail, please consult the White Paper that accompanies this seminar, or the following:

- C. A. Baone and C. L. DeMarco, "Observer-based distributed control design to coordinate wind generation and energy storage," in Proceedings of *2010 IEEE Conference on Innovative Smart Grid Technologies Europe*, Gothenburg, Sweden, Oct. 2010.
- C. A. Baone and C. L. DeMarco, "From Each According to its Ability: Distributed Grid Regulation With Bandwidth and Saturation Limits in Wind Generation and Battery Storage," to appear, *IEEE Transactions on Control Systems Technology*,
  IEEE Explore link:
  http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6142123&tag=1
- C. A. Baone and C. L. DeMarco, "Distributed Control Design to Regulate Grid Frequency and Reduce Drivetrain Stress in Wind Systems Using Battery Storage," to appear, *Proceedings of the 2012 American Control Conference*, Montreal, CANADA, June 2012.

Conclusions/Take Away Points

Key premises underlying this work:

- Renewable generation, coupled to the grid through power electronic interfaces, presents dynamic terminal characteristics very different than those of traditional turbine-driven synchronous machines.

- Dynamic differences become particularly relevant as renewables contribute in grid primary & secondary frequency/power control.

- Added differences in architecture: much larger numbers of individual contributors, operating within narrower +/– MW limits.

- Properties above will likely also be seen in other emerging contributors to “smart” grid control: new storage technologies and responsive load.

Conclusions/Take Away Points

Consequences for control design:

- Dynamic observation of system state will become more important as a component of feedback control. We should exploit control opportunities enabled by wide bandwidth PMU measurements.

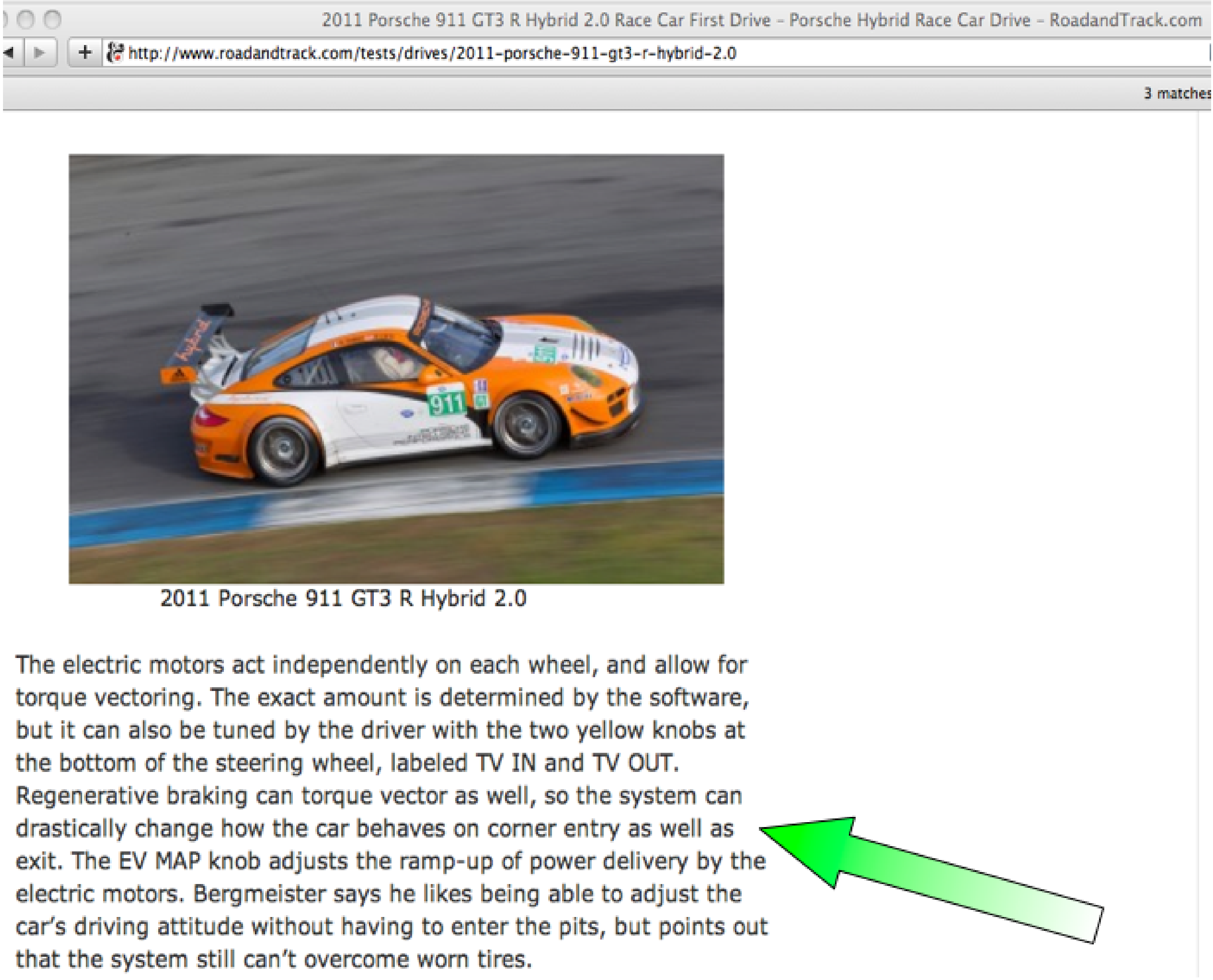
- To manage the diverse dynamic characteristics of renewables, and their inherently more distributed architecture, optimal-control-based designs will become more important.

- As illustrative proof of concept, work here has examined a standard IEEE test system topology, augmented by WECC type-3 models for wind generators. In this (admittedly limited) example, displayed ~100x improvement in frequency regulation against periodic disturbances, while simultaneously reducing torque stress in wind turbine drive train.

Closing Analogy… Automotive Technology

- As analogy to renewables as new class of MW actuators on grid… Consider a new class of "braking torque actuator" in automobiles. In contrast to mechanical frictional force of disk or drum brakes, we now also have electromagnetic torque of regenerative braking.
- How should one use this new class of actuator? (as in our power grid case, obvious it has very different dynamic characteristics!)
- First step – make this new class of braking actuator behave much like traditional technology. From pedal force as "command input," to achieved braking torque at wheels as output, make brakes "feel" same as traditional disk brakes (observe analogy to inertial control).
- As a loyal Road & Track subscriber, the author can report this is largely what mainstream automotive vendors are doing today. With more imagination, what ***might*** we do better…

What Should the Future Hold?



2011 Porsche 911 GT3 R Hybrid 2.0 Race Car First Drive - Porsche Hybrid Race Car Drive - RoadandTrack.com

http://www.roadandtrack.com/tests/drives/2011-porsche-911-gt3-r-hybrid-2.0

2011 Porsche 911 GT3 R Hybrid 2.0

The electric motors act independently on each wheel, and allow for torque vectoring. The exact amount is determined by the software, but it can also be tuned by the driver with the two yellow knobs at the bottom of the steering wheel, labeled TV IN and TV OUT. Regenerative braking can torque vector as well, so the system can drastically change how the car behaves on corner entry as well as exit. The EV MAP knob adjusts the ramp-up of power delivery by the electric motors. Bergmeister says he likes being able to adjust the car's driving attitude without having to enter the pits, but points out that the system still can't overcome worn tires.