Scalable and Flat Controls for Reliable Power Grid Operation with High Renewable Penetration

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Final Report from the Tufts University team

(part of a multi-university team, including additional researchers from Northeastern University, the University of Tennessee, the University of Illinois, and Rensselaer Polytechnic Institute)
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**Abstract**

This project envisions a fundamental shift in the approach to the electric power infrastructure with both a broadening of the electric grid to consider overall end energy use and a “flattening” of the control structure at all levels of the power grid the traditional control strategies. In particular, the research of the Northeastern/Tufts team concentrates on wide-area monitoring and estimation techniques for geographically-distributed electric power systems, with a special focus on mitigating the adverse effects of communication delay and information packet loss, adaptive power-flow control, and fault location from synchronized wide-area measurements. Coordination across wide areas is critical to ensuring that the future grid can enable efficient, low cost and reliable integration of renewables. As such, the work is a system development investigating several areas of control and communications, device technologies as well as electricity market structures. Commonalities arising across these diverse research tasks include the importance of new measurement technologies, increased functionality at the device level and managing uncertainty in both control systems and markets. More specifically, new phasor measurements are used in this work to enable wide area control of the power grid and understand system limits more precisely. Synchronized measurements are used also to locate short circuit faults occurring in the system. New power electronic functionality, both at the source and load, allow improved stability and voltage control. These functions will allow alternative sources to provide grid services to offset their higher costs. Managing uncertainty in the networked estimation and control systems, as for example we do with our delay mitigation scheme, improves reliability and thus, allows greater penetration of renewables. There has been continued rapid growth in renewable interconnections to the grid and the need for improved controls has become critical. These interconnections also necessitated novel ways of protection against system faults given the possibility of reverse flows on certain lines. This third year report details continued progress in understanding the fundamental controls, monitoring and communication structure needed to enable the needed wide area protection and control.
Introduction

Frequently overlooked in discussions on energy problems is the central role that the electric power system infrastructure must play in any viable solution. Power generation plants are among the largest sources of greenhouse gas (GHG) emissions and in addition, many of the proposed solutions for minimizing emission – wind farms, solar roof-tops, plug-in hybrid cars, even the “hydrogen” economy – must rely heavily on the grid. Historically, energy systems have been engineered according to the separate industry sectors, i.e., transportation, heating, electric delivery, and thus, represent “frozen accidents.” Today, a comprehensive solution to the reduction of GHG requires a more general approach. This is not only to avoid shifting problems between sectors but also to take advantage of efficiencies that can only be realized through interaction among the subsystems. The electric power grid must function centrally to this system of systems. Global warming concerns, rising fossil fuel costs, and management of a carbon constrained economy will require the development of a different type of electric power system infrastructure while electric energy resources based on renewable resources and storage are expected to be pervasive. Overall, energy delivery by electricity has great advantages in terms of ease of energy transformation, precise control capability and flexibility for end use – i.e., heating, cooling, lighting, consumer electronics, heavy industry, and so on. The modern electric power grid is extremely reliable and efficient in delivering bulk energy from large-scale sources to load distribution centers. At a high level, the interconnected power grid is reliable because system operators can depend on controllable equipment, e.g., generators, to supply power to meet relatively predictable loads. Unfortunately, many of the renewable technologies pose great operational difficulties because the present system is a centralized control structure with a limited amount of storage and control options that requires a precise balance between load and generation to be maintained at all times.

The main challenges of operating a power grid with a high proportion of generation based on renewable resources include that these resources: (1) are less predictable than traditional fuel based power plants, (2) may be far from load centers so power may have to flow through congested transmission paths, (3) do not generally match the daily cycle of load variation, (4) suffer from unusual operating constraints, such as, rapid variation or complicated weather dependence, and (5) need to be tightly coupled to storage, which may be mobile. To respond to this challenge, this research envisions two fundamental shifts in the approach to the electric power infrastructure, namely

- A broadening of the electric grid to consider overall end energy use, so that electric power generation and delivery does not merely respond to load demand but actively controls energy delivery for plug-in vehicles, the production of fuels (e.g., hydrogen), production of power versus commercially sold steam at thermal plants, energy storage, and end demand as needed.

- A “flattening” of the control structure that fully changes, at all levels of the power grid, the traditional control strategies. Existing energy systems today are characterized by multiple, largely autarchic control systems, including such systems as transient stability control, load frequency control, voltage control, power quality control, and distribution protection. These need to be replaced by a simpler, flatter structure with a local control operating within a more global context for the system.
The research of the Northeastern/Tufts group within the multi-university team associated with this project focuses mainly on the “front end” of the proposed wide-area networked control system, namely on extraction of information from a set of wide-area measurement devices (including phasor measurement units) with application to robust dynamic state estimation and rapid fault location.

**Background**

Wide-area power system protection has been investigated since the first introduction of synchronized measurements. New methods typically aim to optimize system-wide protection actions in order to avoid cascading outages.

**Results**

The numbering of subsections refers to the task numbers in our original proposal.

1.3 *Estimation and control over networks*

Communication delay is one of the unavoidable side-effects of using a computer network to interconnect sensors, actuators and control centers/nodes. In general, increased delay in a feedback control system often results in instability or reduced performance [1]. In [2], we have proposed a delay compensation approach based on time-stamping of transmitted signals, which can successfully mitigate the destabilizing effects of delay. By “time-stamping” we mean that every signal sample \( x(t) \) is transmitted over the network as an ordered triplet \((x, t, k)\), consisting of the sample value “\( x \),” the corresponding sampling time instant “\( t \),” and the identity of the source of the signal \( x(t) \) (e.g., which sensor). Time stamping is enabled by the availability of precise time signals derived from the Global Positioning System (GPS) in various nodes of the power system. Such signals are part of Phasor Measurement Units (PMUs) that are increasingly being deployed as a key ingredient of system-wide monitoring and control.

Time-stamping of transmitted information can be used to overcome random, time-variant, delays in the both the observation path between sensors and estimation hubs, and the control path between the estimation hub and the controller/actuator. It can be used with any state-estimation method and any feedback-control strategy, not just Kalman filtering and LQG state-feedback control. In particular, robust estimation and control methods (see, e.g., [3, 4, 5, 6]) are required to accommodate significant uncertainty in system parameters (and models). Endowing such robust estimation and control techniques with delay mitigation capability is the key to successful implementation in spatially-extended power systems. Recently, we have developed a robust delay mitigation technique, based on the robust estimation algorithm described in [5], which can tolerate high levels of parameters inaccuracy in state-space model descriptions.

For illustration, we show the performance of our robust estimation scheme for the case of a 2-state linear system with uncertain model parameters. Fig. 1 shows the relative
error covariance as a function of the network delay for the accurate model (bottom trace) and for three levels of parameter inaccuracy (1%, 5% and 25%). Notice the significant difference (about 10dB) in error level between the performance of a standard Kalman filter, and that of its robust equivalent, in the presence of a 25% parameter inaccuracy. Also notice the almost linear (in dB) increase in error covariance as the length of delay increases. In comparison, we note that the system without delay compensation becomes unstable for a 180 ms delay.

![Graph showing error covariance as a function of network delay for different models and parameter inaccuracies.](image)

**Figure 1**: Robust delay-mitigating control

Previous analysis of the effects of observation intermittency have mostly addressed the problem of dropped communication packets [7, 8], which result in an irregular (random) inter-sample interval with a Bernoulli (i.e., geometric) probability distribution. We have extended these results to the case of arbitrary (non-Bernoulli) multi-sensor sampling patterns [9]. In contrast to the formulation in [7], our results do not rely on coordination between the individual sensors, since we assume the cyber-physical power system to be geographically-distributed over a wide area. Uncoordinated (i.e., statistically independent) sampling and transmission of sensor observations result in enhanced resilience to communication packet loss and cyber-security attacks. In particular, we have demonstrated that staggered sampling - i.e., displacing the sampling instants of individual
sensors with respect to each other so as to reduce the variation of the combined multi-
sensor inter-sample intervals - results in a reduction of the average estimation error
covariance [10].

We established a necessary condition for stability of a continuous-discrete Kalman
filter with irregularly sampled observations [9]. Our stability condition extends [7] and
relates the location of system poles to the region of convergence of the characteristic
function (a.k.a. moment generating function) associated with the random multi-sensor
inter-sample interval. Recently, we have extended these results to include the effects of
both irregular sampling and delay in the measurement path [11].

![Figure 2](image.png)

**Figure 2:** Effect of delay on estimation error covariance

We have also shown that estimation performance depends primarily on the average
delay (see Fig. 2) as well as on the average length of the sampling interval, with a very
minor dependence on the variance and a negligible dependence on higher order moments
of the (time-varying) sampling interval (see Fig. 3, where $\xi$ is the normalized variance of
the random sampling interval and $\lambda$ controls kurtosis). These observations lead to a
simple design rule: the average sampling interval $T_{av}$ can be adjusted to achieve an
acceptable level of state estimation error.
Figure 3: Effect of statistics of sampling interval on SEER (top) and zoom-in (bottom)
1.4 Modeling and control via dynamic phasors

Dynamic phasors are finding increasing use in analysis and control of electric energy components and systems. Applications of the dynamic phasor framework are numerous, and include power systems (analysis of unbalanced faults and protection), electric drives (analysis of unbalanced electric machines and of position-dependent loads, torque ripple minimization) and power electronics (model reduction in DC/DC converters, analysis of resonant and high-power converters, control of active filters). While dynamic phasors are intended for near-to-periodic operation, they have a number of useful features: (i) models are time-invariant (autonomous); (ii) inputs and consequently states tend to vary slowly compared to the driving frequencies; (iii) they achieve "simultaneous demodulation" in that all variables are constant ("dc") in a steady state; (iv) they are very effective in revealing dynamic couplings between various quantities, as shown in derivation of novel equivalent circuits for unbalanced ac machines [12].

![Figure 4: Customized pre-detection filter vs. wavelet transform (Daubechies)](image)

We have shown that such dynamic phasor expressions are a special case of a broader family of customizable signal transforms that we called *Phasor Banks* [13, 14, 15]. The need for compact dynamic phasor representations that can be efficiently communicated across a spatially distributed cyber-physical energy system mandates customization that focuses on frequency selectivity. Similarly, dynamic phasors for fault detection and location applications require a customization focused on time selectivity. For instance, we have developed an efficient procedure for customization of the pre-detection filter used in fault location in power grids [16, 17]. Our customized pre-detection filter is superior, in terms of both peakedness and group delay, over the currently used (Daubechies-based) discrete-wavelet transform processing of fault waveforms (Fig. 4).
In [15] we presented a method for application-specific customization of dynamic phasors, intended for use in wide-area monitoring and control of electric power networks. We provided an explicit compact characterization of the optimally-robust reconstruction stage of this transform, which can be used with any (customized) choice of its analysis stage. Since the phasor bank transform allows causal delay-free perfect reconstruction of any input waveform, it is perfectly suited for (closed-loop) control applications.

In this project, we continue to explore the advantages of matching phasor bank transforms to different applications, such as fault detection and location, power decomposition, adaptive compensation and networked estimation.

1.5 Dynamic power analysis and control

Our approach to dynamic characterization of power quality, motivated by our steady-state decomposition [18], uses a novel dynamic (i.e., time-variant) 7/11-component power decomposition [19]. Our approach is based on dynamic phasors, and relies on the fundamental, cyclic mode of operation of all energy conversion systems (periodic in the idealized steady-state) and applies naturally to any number of phases. It includes explicit models of components, and reduces to well-known quantities (such as harmonics) in steady state. Such quantities are often the subject of binding regulations (e.g., the power factor or the harmonic content). The quantities that we define dynamically can be used both in simple integral controllers and in more ambitious model-based control schemes. In addition, dynamic phasors can be customized to optimize specific properties in transients (e.g., frequency separation), as shown in [13]. Our dynamic power decomposition, viz.,

\[
S^2(t) = P^2(t) + N^2_s(t) + N^2_u(t) + Q_B^2(t) + Q_s^2(t) + Q_u^2(t) + S^2_\perp(t)
\]

captures transient behavior, while reducing to the standard (constant phasor) characterization in steady-state [19, 20]. Here, \( P \) denotes the real (active) power, \( Q_B \) is the reactive (Budeanu) power, \( N_s \) (respectively \( Q_s \)) is the co-active (resp. co-reactive) power due to the spread of (incremental) conductances (resp. susceptances) in various phases over frequency, \( N_u \) (respectively \( Q_u \)) is the co-active (resp. co-reactive) power due to the spread of (incremental) conductances (resp. susceptances) in various phases across phases, and \( S_\perp \) denotes a component due to system responses (typically currents) at frequencies or phases when there is no driving term (caused by circuit nonlinearity). The use of dynamic phasors makes it possible to enforce \( P(t) = S(t) \) (with negligible line impedance) even during transients, by employing the adaptive compensator of [21, 22], which we describe below.

The role of compensation in controlling power flow in cyber-physical energy systems is to reduce the power consumption of the Thevenin equivalent source (or "line") impedance, so that most of the generated power is delivered to the load. This impedance represents the combined effect of all power sources, loads and transmission/distribution lines in a power network. With the dispersion of energy sources to lower-voltage networks, the line impedances are bound to increase. They will also vary much more, as the topology changes are much more frequent is such networks. In addition, many
renewable sources are inherently single phase (e.g., small rooftop photovoltaics), and their intermittency will lead to increased unbalances in polyphase networks. Together with increased injection of harmonics by new loads and sources, this will result in modes of operation that are qualitatively very different from the ones assumed traditionally for network compensators such as active and passive filters and shunt capacitors.

Traditional compensation methods, such as Fryze compensation, lose their effectiveness when the equivalent line impedance is no longer negligible in comparison with the load impedance. Moreover, constantly changing network conditions require continuous readjustment of the compensator current in order to ensure continuing efficient operation of the power system. We have introduced an adaptive near-optimal compensation scheme that relies only on measurements of the load voltage and current or, equivalently, on the phasor description of these waveforms [21, 22]. Our compensator tracks variations in both network and load conditions, continuously adjusting the polyphase compensator current so as to reduce the power dissipated in the source impedance, for both linear and nonlinear loads.

We show in Fig. 5 an example of the performance of our adaptive near-optimal compensation method: $P_{\text{line}}$ are the line losses, $P_{\text{load}}$ is the power supplied to the compensated load, and $P_{\text{comp}}$ is the (real) power supplied by the compensator (which is zero on the upper parabolic cross-section curve). The nonlinear (electrical) load to be compensated is an induction machine rated at 25 kW, connected to a mechanical load with a quadratic torque-speed characteristic, and supplied over a long, unbalanced line [22]. The solid line in the figure connects the points obtained by our iterative algorithm. We use the cross-section curve, which indicates the theoretical optimum (dash-dot line in Fig. 5) achievable with exact knowledge of network and load characteristics, as a benchmark for comparison. Due to the near-optimal characteristic of our compensator it is observed that the steady-state points (white circle markers in Fig. 5) lie very nearly on the optimum cross-section curve.
In the previous project year we have demonstrated the stability of our adaptive compensation technique in the presence of both linear and nonlinear loads. We have established the boundaries of stable steady-state operation, and developed safeguards against loss of stability. In particular, we have shown that stability of linear loads can be described in terms of “stability circles” (Fig. 6). For nonlinear loads we have constructed an online stability monitor that uses the history of load current and voltage phasors for each mode to determine limiting values for the control parameters of our adaptive compensator (Fig. 7).
**Figure 6:** Stability regions of our adaptive compensator for a linear load.

**Figure 7:** Adaptive online stability monitor.
In this year of the project we have extended the notions of reactive and inactive powers to sub-cycle quantities. This is important for applications where speed of detection of transient variations is paramount.

Given any polyphase (row vector) waveform $x(t)$ we define a Sub-Cycle (or near-instantaneous) dynamic phasor $\hat{X}_1(t)$ as

$$\hat{X}_1(t) = \frac{1}{\sqrt{2}} e^{-j \omega t} \left[ x(t) + j x(t - \frac{T}{4}) \right]$$

where $\omega = 2\pi / T$ denotes the fundamental frequency.

This definition, while simple and easy to implement, leads to dynamic apparent power decompositions that outperform [23] the widely-used “instantaneous reactive power” of Akagi [24]. We illustrate this point on an industrial load that undergoes an unbalanced transitory fault.

**Figure 8:** Sub-cycle power components (solid red line) vs. instantaneous power components (dashed blue line)

**Micro-grid Modeling and Control Architecture**

In the last year of the project, we have used the previously developed tools to advance modeling of micro-grids for control purposes [25]
Figure 8: Schematic representation of a microgrid. The microgrid is composed of several DG units, loads and storage devices. The DG units are inverter-interfaced photovoltaic (PV), fuel cell (FC) and wind power plants. In addition, a power generation unit is connected to the network via a synchronous generator (SG). The point of connection of the microgrid to the main network is called point of common coupling (PCC).

We have also identified a control structure that underlies many existing controllers in power systems, as it combines global signals from the grid with signals communicated locally and globally (through the communication network).

Figure 9: Schematic representation of a prototypical control architecture for coordinated grid operation
Conclusions

**Networked Dynamic State Estimation:** We developed a continuous-discrete Robust Kalman filter, and applied it to reduce the effect of network delay. Our robust state estimator relies on time-stamping technique to mitigate the destabilizing effects of network delay in the presence of significant model parameter uncertainty. We also demonstrated the reduced sensitivity of our robust estimator to such uncertainty as compared with the standard Kalman filter. In particular, we have shown that our robust dynamic state estimator can successfully counter the effects of latency in feedback-stabilized systems: stability is maintained, at the cost of increased estimation error, even in the presence of model parameter inaccuracy, as well as significant (and possibly time-variant) delay in the feedback loop.

**Adaptive Power-Flow Control:** We have developed an adaptive near-optimal compensation scheme that relies only on measurements of the load voltage and current or, equivalently, on the phasor description of these waveforms [21,22]. Our compensator tracks variations in both network and load conditions, continuously adjusting the polyphase compensator current so as to reduce the power dissipated in the source impedance. We demonstrated that our adaptive load compensation algorithm remains stable, while providing near-optimal power-flow control, for a very wide range of its control parameters when used with either linear or nonlinear loads. We have examined the stability and transient behavior of the iterated function map that is defined by our adaptive compensator, and demonstrated that this iterated function map is, in general, locally exponentially-stable for a suitably restricted range of its control parameters, when used with either linear or nonlinear loads.

**Generalized Dynamic Phasors:** We constructed a comprehensive framework for customization of dynamic phasors, with a special focus on frequency-selective design for networked estimation and control, and time-selective design for fault detection and location. We also introduced a new metric for waveform peakedness and demonstrated its utility for designing time-selective phasor banks. When applied to power system fault waveforms, our optimized dynamic phasors outperform standard (Daubechies) wavelets in terms of both peakedness and group delay.

A dramatic reduction in the environmental impact of power generation and distribution can come only from improvements in the energy flow layer: incorporation of significant storage and sustainable power sources (e.g., wind, solar). However, the information/control layer of existing power networks is often fragmented and mostly uncoordinated. As such, it is particularly ill-suited to handle novel and volatile power flow patterns that will likely arise with increased penetration of intermittent sources such as wind and solar power. Many perturbations and faults in energy flow can be traced back to the inadequacy of the sensing, estimation and control techniques used in present day power networks. Our analysis suggests that networked estimation/control could be a viable approach to remedy some of the deficiencies in information processing and control for existing electrical power systems, integrating sensing, state/parameter estimation and
control to facilitate effective (high-level) control of energy flow. We envision increased couplings among dynamic components in several frequency ranges, which will in turn necessitate development of new coordinated control algorithms, possibly aided by formal verification methods. We also envision the need to use real-time measurements to identify key dynamic parameters on-line, such as inertias, load characteristics and available storage behind the customer interfaces.
Publications resulting from work on this project


References


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