The modernization of the power grid is driven by two major trends: the increasing penetration of renewable generation, and the integration of information technologies and advanced power electronics. The former trend introduces large, rapid, and frequent variations in power supply, making it costly to stabilize the grid. The latter trend creates a tremendous number of distributed endpoints such as smart buildings and appliances, electric vehicles, storage devices, and inverters that can sense, compute, communicate, and actively participate in power system control. The goal of my research is to exploit endpoint-based control to enhance power system robustness and efficiency in the presence of highly volatile renewable generation. My previous research focused on distributed frequency control, where I have established a theoretical framework for controller design and stability analysis in dynamic power networks. Moving forward, I aim to build an endpoint-based control architecture to overcome challenges from the decreasing inertia and increasing heterogeneity of future power systems, taking into account practical issues on information acquisition, communication, et cetera. The central approach in my research is to utilize and develop mathematical tools from control, dynamical systems, and optimization to interpret physical laws and improve engineering mechanisms of power systems. Combining this approach with empirical studies, I will cultivate a research program that thrives on foundational theories and rigorous analysis, and has a real impact on the power industry. In the future, the tools developed in my work can be adapted for more general networked control systems and cyber-physical systems, and hence make contributions to a wide spectrum of application fields.

1. Previous research: Distributed frequency control

Frequency control stabilizes frequency and restores it to the nominal value when power supply or demand fluctuates. It is currently implemented primarily on the generators, which are inefficient in terms of fuel and emission costs. These costs will only increase with higher renewable portfolio and may essentially neutralize the benefits of renewables. A promising solution is to exploit smart buildings and appliances, electrical vehicles, storage devices, inverters, etc. as participants in frequency control. These participants are mostly distributed on the load side of the grid, and can deliver cleaner, faster, and more spatially precise response to frequency fluctuations, compared to generators. While simulation studies in academia and field tests in Pacific Northwest National Lab, UK Market Transformation Program, PJM, etc. have demonstrated effectiveness of this solution, the lack of a systematic method for controller design and stability analysis is still a major hurdle that must be overcome before its large-scale deployment. My research addresses this issue by establishing a novel design and analysis framework for distributed frequency control, in two directions.

Direction 1: Optimization-based controller design

In [1] we proved that the swing dynamics of synchronous generators, the linearized power flows, and the droop control can together be identified as a real-time primal-dual algorithm to solve an optimization problem which, in equilibrium, restores power balance and stabilizes frequency with minimum control cost. It is the first time that this mathematical implication has been revealed. More importantly, this implication enables us to design different controllers to satisfy application-specific requirements, by modifying the underlying optimization and then deriving its primal-dual algorithm. This optimization-based controller design framework has two advantages. First, the underlying optimization and its dual intrinsically have a decomposable structure which leads to decentralized or distributed control laws that are scalable to a large number of load-side participants. Second, the convergence of the primal-dual algorithm to the
optimal saddle point naturally provides a stability proof for the closed-loop system.

Applying this framework to a broad scope of convex cost functions, we designed completely
decentralized primary frequency control where every participant only measures its local
frequency, and no explicit communication is required [2]. By further manipulating the underlying
optimization, we designed distributed secondary frequency control, where every participant
only measures its local frequency and power flows and communicates with its neighbors. This
distributed secondary frequency control not only restores frequency and inter-area power flows
to their nominal values, but also enforces thermal limits of transmission lines such that the
$N-1$ security criterion and chance constraints in economic dispatch can be relaxed, resulting
in significant savings [3].

**Direction 2: Stabilizing nonlinear dynamics**

A linearized model is adequate for frequency control today, but in the future, a more accurate
nonlinear model must be used to deal with high volatility of renewable generation. Stability of
dynamic networks with *nonlinear power flows* was extensively studied, especially around the
70s and 80s, with a substantial body of literature using Lyapunov’s direct method. I extend
this method for distributed frequency control, as elaborated below.

With nonlinear power flows, the optimization-based framework in Direction 1 no longer
provides a straightforward stability proof, since the underlying optimization is nonconvex and
therefore its primal-dual algorithm may not converge. In [4], [5], we performed compositional
stability analysis for the distributed primary and secondary frequency control designed with this
framework. We proved asymptotic stability of the closed-loop system by checking a passivity
condition individually for the physical layer (swing dynamics coupled by nonlinear power
flows), the cyber layer (distributed controllers connected in a communication graph), and each
of the actuators (e.g., generators and controllable loads) interfacing these two layers. This
compositional approach facilitates stability assessment for different power network models,
controllers, actuators, and communication schemes.

My research along this line provides valuable insight into the role of communication in
controlling a network. In [6] we proved that completely decentralized frequency integral control
without any explicit communication *globally* stabilizes a network with nonlinear power flows
to an equilibrium with nominal frequency. However, this completely decentralized control is
sensitive to local measurement noise, and may incur large and suboptimal control actions.
We improved this control by adding distributed consensus filters based on communication
between neighbors. These filters ensure that, in equilibrium, the marginal control costs are
equal for all the participants, thus minimizing the total cost of control. In addition, distributed
communication is able to mitigate the negative effect of measurement noise, as shown in our
earlier studies [7], [8]. Intuitively, a tradeoff must be made between communication cost and
controller performance.

**Impact of my research**

My paper [2] has been cited more than 50 times since May 2014. The idea in this paper has
been applied by other researchers in improving economic efficiency of automatic generation
control (AGC) [9], reverse-forward engineering of power systems [10], and so on. An important
application of distributed frequency control is *load-side* participation. In simulations of IEEE
systems on Power System Toolbox, we showed that the load-side distributed frequency control
significantly improves system performance compared to AGC. Based on this idea, Caltech
has filed a patent, and our proposal received the Qualcomm Innovation Fellowship Finalist
Award. The inventors of IBM nPlug, the operators of FNET, and the startup Energy Adaptive
Network have shown great interest in helping us with its prototype implementation.
2. Future research: Endpoint-based control architecture for power systems

The results described above establish a preliminary intellectual foundation for distributed frequency control, or more generally endpoint-based control. Converting this idea to real-world applications will require a coherent architecture to integrate the proposed control. Centered around this topic, my efforts will continue in two directions, as discussed below.

Direction 1: Extending controller design for the future grid

The ongoing transformation of the grid brings new challenges to controller design. First, the current system models and theories must be greatly extended, due to the following trends. (i) The controllable endpoints and renewable energy resources are connected by various power electronics, increasing the heterogeneity and decreasing the inertia of power systems. (ii) Larger variations in renewable generation may trigger tap changers and protective relays more frequently, causing discrete state transitions. (iii) The traditional power flow model has to be modified in the flexible alternating current transmission system (FACTS) and the high-voltage direct current (HVDC) system. The previously described theoretical framework should be extended to accommodate these trends. In particular, I will focus on distribution systems, especially microgrids, where the heterogeneity is most significant.

Second, transient performance becomes more important. A power system with lower inertia is more likely to suffer drastic overshoots and oscillations, even when it is stable. Hence transient performance needs to be taken into consideration during controller design. Specifically, I will design endpoint-based oscillation-damping control through eigenvalue or mode analysis. On a parallel way, I am going to formulate and solve model predictive control (MPC) problems whose objectives include accumulated frequency deviation, frequency nadir, convergence time, or other measures of transient performance.

Direction 2: Integrating control, information acquisition, communication, and more

Information acquisition serves as the input to power system control. It consists of measuring electric signals such as voltage, frequency, power, etc. and acquiring system parameters including the network topology. Electric signals may be sampled at low rates or without a global clock. This motivates the study of robustness of endpoint-based control to low time-resolution or asynchronous measurements, on which we have a preliminary result [11]. Moreover, the measurements may not be available at every network bus, in which case an investigation of system observability and detectability is necessary. Furthermore, I would like to design endpoint-based controllers that are robust to errors and uncertainties in system parameters, and develop system identification schemes using historical or online measurements.

Communication plays a vital role in endpoint-based control. On the one hand, the communication topology should be codesigned with control laws and controller placement, subject to availability of sensors, control devices, and communication infrastructures. I am particularly interested in formulating and solving a sparsity-constrained optimization for this codesign. On the other hand, loss and latency along communication channels impose additional conditions on control parameters, e.g., feedback gains, for the closed-loop system to be stable. I intend to characterize these conditions, applying ideas from the research on Internet congestion control [12] and coupled oscillators [13].

The current modus operandi of power systems relies on generator-side mechanisms including automatic voltage regulation (AVR), power system stabilizer (PSS), droop control, and AGC. Any novel control scheme can only be introduced as a supplement to these mechanisms, and deployed in an incremental fashion. Therefore it is important to investigate the interactions between endpoint-based control and generator-side control. My earlier work [8] incorporated AVR, PSS, and droop control into a higher-order generator model when designing distributed frequency control. A more fundamental question is whether centralized (e.g., for AGC) and distributed
control structures can coexist in one system and work in concert for better performance.

Last, I would like to coordinate endpoint-based control and economic dispatch. As exemplified in [3], the distributed frequency control benefits economic dispatch by enforcing line limits and thus relaxing security constraints. To fully capture this benefit, I plan to carry out three tasks. The first is to develop stability-promoted distributed control which can handle larger deviations from the equilibrium, expanding the tolerance region of security-constrained economic dispatch. The second task is to optimally allocate resources between economic dispatch and endpoint-based control, considering the speed of response, ramp rate, capacity, and operating cost of each resource. The performance improvement from such allocation is observed in my previous work on Volt/Var control [14]. The third task, motivated by a recent study [15], is to design market mechanisms which implement economic dispatch while providing appropriate incentives for endpoint-based control.

Concluding remarks

The power grid is rapidly evolving, so is its control architecture. My research will not only establish an intellectual foundation for, but also make practical contributions to, this architectural evolution. With this belief, I will move forward through theories, algorithms, simulations, and prototypes, paving the way to industrial applications.

References