RESEARCH STATEMENT

JASON POON

I am broadly interested in fundamental challenges that arise when power electronics are connected in networks—both in localized contexts (e.g. modular multiphase power converters) and in highly distributed contexts (e.g. grid-interfaced renewable energy). My research explores power electronics simultaneously from a circuits and systems perspective. I leverage fundamental theory from an array of interdisciplinary domains—including decentralized optimization, networked control systems, and statistical signal processing—to develop revolutionary power electronics circuits and network architectures that are validated with industry-quality hardware prototypes. In particular, my doctoral dissertation introduced and validated the notion of ***system-aware power electronics***, that is, power electronics that are *designed in tandem* and adaptively *co-optimized* for each other and the system they are a part of—and can offer transformative leaps in performance, efficiency, resiliency, and power density. My vision is to translate these technical innovations into practical and scalable solutions to emerging societal-scale challenges in renewable energy, electrified transportation, miniaturized and on-chip power, wireless power transfer, and energy infrastructure and distribution.

System-Aware Power Electronics

We are entering an era when power electronics no longer form niche parts of power networks, but rather, handle a majority or all of the power processing functionality. For instance, dc power distribution is an emerging power electronics-enabled architecture that promises substantial efficiency improvements in buildings, electric aircraft, and microgrids. Conventional approaches often treat power electronics modeling, circuit design, and control in a black-box sense, with numerous hardware and software techniques used to minimize detrimental or unwanted interactions among power converters. However, as networks scale to include potentially hundreds or thousands of interconnected power converters, the conventional thinking reaches fundamental limits in terms of overall complexity, reliability, efficiency, and power density—ultimately inhibiting the achievable functionality and scale of these systems.

To address this challenge, I develop power electronics circuits and systems that incorporate the electrical network interconnection—and the associated coupling and interactions that naturally arise—as an integral part of the analysis, circuit design, and control process. The resulting *system-aware power electronics* obviate the limits of a black-box design approach, and demonstrate enhanced performance, efficiency, and reliability for the power converters *and* the overall system. To date, I have pioneered design techniques for miniaturized power electronics circuits that operate *in tandem* with each other to enable vastly improved power quality, efficiency, and fault tolerance [1, 2]. Moreover, I have developed power converters that can actively detect and diagnosis faults—essentially acting as *probes* within networks—enabling order-of-magnitude improvements in reliability and resiliency [3, 4, 5]. These projects, described below, have resulted in publications, funding, and new collaborations with industry, national laboratories, and academic institutions.

1. Minimum Distortion Point Tracking

Power converters are designed with filtering, buffering, and EMI stages that account for a dominant portion of their overall cost, size, and complexity—all of which scale unfavorably as networks grow to accommodate more power domains with a diversity of energy sources and loads. During my Ph.D., I introduced and experimentally validated the notion of *Minimum Distortion Point Tracking*, a strategy where the switching waveforms of distributed, interconnected power converters are *optimally* and *dynamically* phase shifted to minimize the aggregate harmonic power [1]. By realizing power-quality improvement through control, the design of filter, buffer, and EMI stages in *every* power converter can be drastically minimized, and in some cases, removed entirely, facilitating network-wide improvements in efficiency and power density. For networks with just three interconnected converters, Minimum Distortion Point Tracking demonstrates a **10**× improvement in power quality over conventional state-of-the-art techniques. More interestingly, the improvement scales monotonically with the number of converters in the network, implying an opportunity to revolutionize the design of large-scale networked power converters.

2. Next-Generation Modular and Fault-Tolerant Multiphase Dc-Dc Power Converters

Multiphase dc-dc converters are ubiquitous in a variety of applications, including data center power delivery and power management integrated circuits. The modular and redundant circuit structure of the multiphase architecture lends itself to high reliability applications. However, symmetric switch interleaving (i.e. uniform phase-spacing across pulse width modulation carriers) is a necessity for multiphase converters to minimize ripple and passive component size. State-of-the-art interleaving techniques universally require a centralized clock or communication link to coordinate the switching dynamics of each phase, introducing a centralized point of failure that compromises the modularity and 'plug-and-play' nature of these circuits. To address this fundamental limitation, my Ph.D. dissertation developed a first-of-its-kind *decentralized* and *communication-free* technique for interleaving in multiphase dc-dc converters [2]. By embedding the dynamics of a Liénard-type oscillator (a more general form of the well-known Van der Pol oscillator) in the feedback control of *each* phase, the aggregate multiphase converter exhibits a form of injection locking that enables precise and ultra-fast switch timing coordination. I designed and built a 600 W multiphase dc-dc converter embedded with the proposed technique, and, to the best of our knowledge, presented the world's first experimental demonstration of symmetric switch interleaving that is completely communication-free. This proof-of-concept prototype lays the foundation for highly modular and fault-tolerant converters for a variety of key applications, including on-chip and point-of-load power conversion.

3. Power Converters as *Probes* to Enable Resilient and Secure Networks

Large-scale power electronics networks pose a number of interesting challenges with respect to reliability, security, and safety. Towards this end, my Ph.D. work developed fundamental techniques to design power converters as multifunction devices that—in addition to processing power—can act as *probes* that actively monitor themselves *and* the networks that they are connected to [3, 4, 5, 6]. My work in [7] was among the first to demonstrate fast and practical *real-time* adaptive estimation techniques for switching power converters through innovations in switched linear state estimation algorithms and efficient FPGA implementation. Building on this, I developed *FailSafe*, a family of computationally-efficient algorithms for fault detection and diagnosis [3, 4]. FailSafe provides fast detection of critical faults, is generalizable to arbitrary topologies, and provides precise and localized information in large-scale power electronics networks. Taken together, FailSafe aims to embed reliability at the *edge* of distributed networks, and has been demonstrated to enable order-of-magnitude improvements in overall system resiliency and uptime. FailSafe has been recognized with a Best Paper Award at COMPEL 2016 [5], and is currently part of an on-going collaboration with the University of Washington through a newly acquired 3-year, $2.8M DOE-funded project for modular string inverters in photovoltaic systems.

Research Agenda

My vision for the next decade is to expand my work broadly into areas of power electronics and energy systems with opportunity for high societal impact. In particular, some areas I am interested in include:

1. System-Aware Power Electronics for High-Impact Applications

In many current- and next-generation electricity networks, power electronics will handle a majority or all of the power processing functionality. For instance, commercial buildings with dc power distribution can offer greatly improved energy efficiency, as well as superior flexibility in the integration of renewable energy, storage, and on-demand loads. In these contexts, I am excited about the design, control, and optimization opportunities that are made possible by system-aware power electronics. I envision power converters that can be orders-of-magnitude smaller and more capable than current state-of-the-art technology by leveraging online decentralized consensus optimization techniques. I also envision new power distribution architectures that can be resilient *by construction*—enabling a new generation of highly secure and scalable power networks. The scope of this work is highly interdisciplinary, drawing from domains including circuit design, control and optimization, and power system dynamics and stability. I anticipate that this project will be the cornerstone of a multi-year, multi-million dollar NSF or DOE proposal, and in the first few years of my appointment, one of my priorities is to establish the research team and collaborators needed to make this a reality. For instance, the 2018 $20M DOE EERE award program titled "Advanced Power Electronics Design for Solar Applications" would have been a prime funding opportunity for this research direction. This research would also be suitable as an NSF CAREER or Air Force Young Investigator Program proposal. In the near term, I am collaborating with staff scientists at Lawrence Berkeley National Laboratory to explore these concepts for commercial building applications and to develop standards that could make these techniques readily available for widespread industry adoption.

2. On-chip Power and Miniaturized Circuit Topologies for Artificial Intelligence and IoT

Emerging megatrends such as artificial intelligence and IoT are creating a critical need for efficient, scalable, and miniaturized power infrastructures that are suitable for the unique demands of these applications. For instance, artificial intelligence applications rely on power-hungry silicon that is always-on and highly parallel (e.g. [8]), while IoT systems require compact and efficient methods for wireless power transfer or energy harvesting. I am interested to explore these research problems from a simultaneous *power* and *system* perspective—I believe that designing with power as a first-class principle will enable new system architectures that are higher performance and more efficient than what is achievable today. My work on Minimum Distortion Point Tracking shows that there is considerable opportunity to improve circuit design when adaptive online optimization techniques are employed on a broad scale. I am currently collaborating with Dialog Semiconductor on a multi-year project to leverage these principles to design a fundamentally new architecture for wireless power transfer—a novel asymmetric multi-level circuit topology combined with a modified Minimum Distortion Point Tracking scheme. Additionally, I initiated discussions with collaborators from Intel on applications for power conversion techniques for highly-parallel and unbalanced processors loads. I intend to fund this thrust of my research through grants from industry collaborations and from federal funding sources such as the recent DARPA Electronics Resurgence Initiative.

3. Emergent Self-organizing Power Converters for Power Systems Control

As power electronics become ubiquitous in transmission and distribution networks (e.g. [9]), the dynamics of power converters at the switch-level offer new opportunities for system-wide control and optimization. Towards this end, I am interested in how the control of *individual* power converters can enable emergent self-organizing system behavior in a decentralized fashion. By integrating such controllers at the converter level, systems can be built from the 'bottom-up', which will enhance modularity and resiliency. Moreover, power electronics provide a fast control actuator capable of novel grid ancillary services such as active power filtering and real-time fault mitigation. To explore these questions, I intend to develop large-scale experiments using hardware-in-the-loop or power hardware-in-the-loop techniques [7, 10], which will enable rigorous system validation with real-time constraints and communication latencies. Moreover, there are interesting research questions regarding the cybersecurity and associated vulnerabilities of these systems. I have started preliminary investigations in these directions with collaborators at the University of Minnesota, the University of Washington, the National Renewable Energy Laboratory.

4. Signal Processing and Statistical Methods for Networked Power Converters

Conventional power electronics control is largely based on periodic uniformly sampled time-domain data. My research in Minimum Distortion Point Tracking piqued my interest in new types of signal processing and statistical techniques that may have unique applications for power electronics control. For instance, online spectral estimation strategies can enable adaptive optimization of high bandwidth frequency information, and sparse or nonuniform sampling can make such techniques practical in terms of realizable sampling and low-cost processing hardware. I believe that such techniques can lead to new perspectives on decentralized power electronics control, and will facilitate an array of new application opportunities, particularly for distributed and heterogeneous power networks.

Concluding Thoughts

The increasing ubiquity of interconnected power electronics offers new opportunities to fundamentally rethink the design, control, and optimization of these circuits and systems. These research questions encompass a rich space of both theoretical and practical perspectives, and aim to address some of the most important and exciting challenges facing our society today.

References

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