“Energy/Power Management Systems”

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1 Introduction to the focus area

Power and Energy Management are areas undergoing important transformations thanks to new information technologies, advances in circuits and control strategies, and new market strategies and regulations. Interactions of power-hungry electronic devices, electric vehicles, alternative energy generators, and the utility grid are complex and require study to ensure power availability and reliability. Moreover, the availability of new power semiconductors offers exciting possibilities for the design of new smaller, more efficient power electronics system.

The goal of this focus group is to explore topics in the areas of power distribution, energy efficiency, power electronics smart grid, optimization, fault-management and security of power systems, etc.

What follows is a brief description of some of the research projects of this group interest.

![Figure 1: Areas of Interest of the Power/Energy Management Focus Area](image-url)
2 Stochastic Optimization for Smart Grid

Dimitry Gorinevsky (EE) and Stephen Boyd (EE)

The growing integration of renewable generation increases random variability of electrical power loads and prices in the power grid. This makes existing analytical methods inefficient and requires new approaches. We work on stochastic optimization in the electrical power market using time series forecasting and stochastic models of the forecast errors. The non-parametric stochastic models are built from historical operation data. Stochastic optimization currently used in power market applications, such as wind power generation, energy storage, power procurement in the day-ahead electricity markets, relies on normal distribution models. At the same time, the demand and spot prices are non-Gaussian; their peaking is described by long tails. We build non-parametric stochastic models from the data; the models do not assume prior distribution shape and account for the long tails. An optimization-based approach is used for simultaneous estimation of multiple quantiles in the joint non-parametric model of the load and the prices. The approach uses the alternating direction method of multipliers (ADMM) and is scalable to extremely large training data sets.

The approach was demonstrated using time series of hourly electrical power loads and spot market electricity prices collected over several years for a US utility. The non-parametric quantile regression models of the proposed form are trained on older historical data, then backtested for stochastic optimization of power purchase decisions in the day-ahead power market. The result is that using the proposed stochastic optimization approach leads to 2% savings compared to the forecasting methods currently used in the industry. With $400B/year bulk electricity sales this is a potentially huge number.

Figure 2: Big Data analytics, non-parametric model, multiple quantile regression
3 Data-driven Risk Analytics for Energy and Climate

Dimitry Gorinevsky (EE) and Stephen Chu (Physics)

The predictive analytics outliers, the anomalous data that defy prediction, represent extreme (peak) events and can be used to study risks to cost, safety, and other critical performance indicators. This work develops methodology for analyzing the risks of these extreme events across the time (longitudinal study) and the populations (cross-sectional study). In modern Big Data problems, there can be thousands of one in a million peak events. This affords detailed modeling of the extreme statistics, the subject of our work. Our methodology is scalable to petabyte size data sets. The trends of extreme event risks are of much interest in problems of climate science, finance, industrial data, and actuarial risk.

Figure 3: Long tail models. Optimal Bayesian estimation. Big Data analytics. Value at Risk. Longitudinal and cross sectional risk analysis. Smart Grid. Climate change.

The branch of statistics describing the rare peak events corresponding to the tails of the probability distributions is known as extreme value theory (EVT). The EVT establishes Pareto (power law) or exponential tails as common long tail distribution. The tails can be estimated using peaks over threshold (POT) method by fitting the model to the threshold exceedance. There is no prior work in the optimal multi-period estimation of long tail models. We develop optimal Bayesian methodology that does that.

The methodology was demonstrated for power grid data and climate data. The results yield non-trivial conclusions about the trends of extreme events and allow estimating changing risks of the extreme events for decision making or actuarial purposes. For the power grid data, these trends
were analyzed across the service zones of the utility. For the climate data, the year-to-year trends of extreme temperature are analyzed across the 12 calendar months of the year.

The global warming trend is well established. The trends of extreme climate conditions are less understood. Peak temperature or precipitation anomalies, which are the deviations from the mean, can be modeled as a random variable. We estimate the trends of extreme event risk for each calendar month across multiple years and show that these risks have been recently increasing. The work on modeling the trends of extreme event risk in changing climate is collaboration with the National Center for Atmospheric Research.

4 Stability of Grid-connected Microgrid

Dimitry Gorinevsky (EE) and Sanjay Lall (EE)

The existing electrical grid was designed for centralized power generation, where the rotational energy of large synchronous generators is used to balance the instantaneous difference between the bulk supply and the demand. The distribution systems are passive, and the voltage profile along a distribution line is a consequence of the power flow from the feeder to the loads.

Emerging distribution systems with distributed energy resources (DER) challenge this paradigm. Solar, battery, and other DER are connected through inverters that do not have the benefit of the intrinsic stabilizing effect of the rotational inertia. Currently, most inverters in the distribution systems use grid-tie control, where frequency and power are not linked. This is prescribed by the
IEEE 1547 interconnect standard under the assumption that DER will provide for a small fraction of the total demand.

The need to support much greater penetration of renewables has led to the introduction of droop inverters, which emulate the response of the generators with rotational inertia using control logic known as the droop control. Droop inverters in a distribution system influence line frequency. Multiple independent inverters interact through the line frequency. This can provide a degree of load balancing in the system. Yet, these interactions may also have unintended consequences, such as excessive frequency swings, power sharing issues, or voltage profile variations. Surprisingly, there appears to be little literature analyzing these important issues.

We develop methods for modeling and analysis of grid-connected power distribution systems with many sources connected through the droop inverters. Our approach allows evaluation of the system stability and its sensitivity to disturbances in frequency, load, and voltage profile. We applied our methodology to distribution systems with up to 150 inverters spread along the line to analyze the voltage profile sensitivity to the distributed generation disturbances and find the inverter control tuning that would guarantee the frequency stability. The methodology is useful in engineering of power distribution systems with a large fraction of inverter-connected DER generation.

5 13.56 MHz 1.5 kW Resonant Converter with GaN FET for Wireless Power Transfer

Juan Manuel Rivas Davila (EE)

Interest in power converters that can deliver kW levels of wireless power is on the rise due to the convenience these systems offer to the owners of an ever growing fleet of electric vehicles [1]. The goal of this project is to evaluate the use of available GaN switching devices to implement a 1.5 kW power amplifier at 13.56 MHz frequency WPT system [2]. In addition to the increasing demand for more efficient power converters, there is also a drive to reduce the size of the power electronic system while maintaining high efficiency. Operating a resonant converter at frequencies above 10 MHz results in converter designs with small passive energy storage components (inductors and capacitors) [3] and corresponding fast transient response.

Silicon (Si) MOSFETs have already been demonstrated as being viable devices for these type of applications. However, Si MOSFETs capable of reaching kW levels of RF power in appropriate low inductance packages are scarce, and the few available devices are lossy and difficult to drive. Specifically, [4] shows a 30 MHz, 1 kW converter using a Si ARF475FL MOSFET, 500 V rating, from Microsemi. In that paper, connecting the input of multiple converters in series reduces the voltage stress across each MOSFET and allows the use of an overall higher input bus voltage to achieve higher output power. The ARF475FL was chosen because of its low inductance package, and relatively low $R_{G}$ and $C_{gs}$, which makes it possible to drive at MHz frequencies. However, these MOSFETs have a relatively large $R_{ds,ON}$ ($\approx 0.8 \Omega$ at $25^\circ C$) which result in higher conduction loss. The advent of wide-bandgap (WBG) devices and their commercial availability promise to overcome many of the pitfalls of Si devices in medium voltage power applications. WBG devices promise better electrical performance and lower device capacitance which can lead to faster switching and improve power densities and efficiency. Specifically, GaN semiconductors are be-
coming widely used in high frequency switching power converters [5, 6]. In this work, we use the GS66508 from GaN Systems Inc. [7]. This device has a relatively high $V_{DS,max}$ (650 V), low $R_{dson}$ (52 mΩ), and very low $C_{iss}$, $C_{oss}$, and $C_{rss}$ capacitance. [8].

Current implementations of high frequency wireless power transfer systems often use resonant power inverter topologies such as half/full bridge, class D, class E, and other quasi-resonant topologies for the transmitter stage [9–13]. However, these topologies either impose high voltage stress on the semiconductor devices (class E, quasi-resonant inverters) or require more than one switching device (half/full bridge and class D) requiring more complex gate driving schemes. Here, we use class $\Phi_2$ inverter with a single ground-referenced switch and relatively low voltage stress on the switch ($\sim 2 \times V_{in}$) [14] to address these issues.

We will work on more experimental measurements of the inverter in a WPT application, characterization of the system performance over various distances and operating conditions, as well as a breakdown of the power losses in the circuit.

![Figure 5: Class $\Phi_2$ inverter. Peak drain voltage is reduced to $\sim 2 \times V_{in}$.](image)

![Figure 6: Class $\Phi_2$ inverter board. $V_{IN}=200$ V, $P_{OUT}=788$ W, efficiency=94.5 %](image)

6 High-power-density AC/DC Converter for Servers

Juan Manuel Rivas Davila (EE)

Large data centers use as much electricity as a small town and sometimes are significant sources of air pollution. High-efficiency and high-power-density server power supplies save both energy and space greatly. Traditional hard-switching switched-mode power supplies operate at frequency range of tens to hundreds of KHz. Innovative resonant power electronic circuits with soft-switching characteristics can push switching frequency to tens and hundreds of MHz, hundreds times higher than the traditional power converters. Much higher switching frequency reduces the sizes of the passive components a lot which take the most space of power converters.

We have successfully built many power converters switching at High Frequency (HF). Figures below show a 480 W, 133 W/in$^3$ dc-dc converter operating at 27.12MHz. It is part of the ac-dc converter for server applications. Experimental results show that wide-bandgap semiconductor devices such as Gallium Nitride (GaN) and Silicon Carbide (SiC) are much smaller than silicon
devices and more suitable for high-frequency and high-power operation, which can push the power density higher.

![Image](image1.png)

**Figure 7**: 480 W prototype Dc-Dc converter, $V_{IN}=170$ V, $V_{OUT}=48.5$ V, $\eta=84\%$, Volume: $4 \times 2 \times 0.45$ in$^3$, power density: 133 W/in$^3$, GaN FET is used in inverter stage, SiC diodes are used in rectifier stage.

![Image](image2.png)

**Figure 8**: Impedance looking into the drain of the GaN FET in the Class $\Phi_2$ inverter.

We have also been trying to apply circuit techniques which have been widely-used in traditional power electronic circuits such as input-parallel-series-output (IPSO) architecture and synchronous rectification to HF power electronics. Synchronous rectification can eliminate the losses due to irremovable forward voltage drop of diodes and increase the efficiency. However, it is difficult to maintain the precision of HF gate-drive signals for synchronous rectification due to the unpredictable parasitics on printed circuit board. We believe custom gate-drive chip can help solve this problem. Besides topological and control advantages, improvements in high-frequency and high-power inductors and capacitor would also contribute to pushing the power density higher.

We believe that pushing switching frequency higher is the fundamental way to push the power density of state-of-art power converters higher and higher. With the help of advancements in resonant power circuit architectures, customized IC fabrication, and improvements in high-frequency passive components, HF power converters will replace the bulky and noisy low-frequency power converters not only for the servers in data centers but also in many applications.

**References**


