Control for Grid Responsiveness

Control room of a transmission system operator

Reliable electricity supply is largely taken for granted in the developed world. Very few electricity users think about the extensive infrastructure that is required to support ubiquitous availability of electrical energy. Even fewer are aware of the sophisticated analysis and control that underpins secure operation of these large-scale, highly-distributed, nonlinear, hybrid dynamical systems.

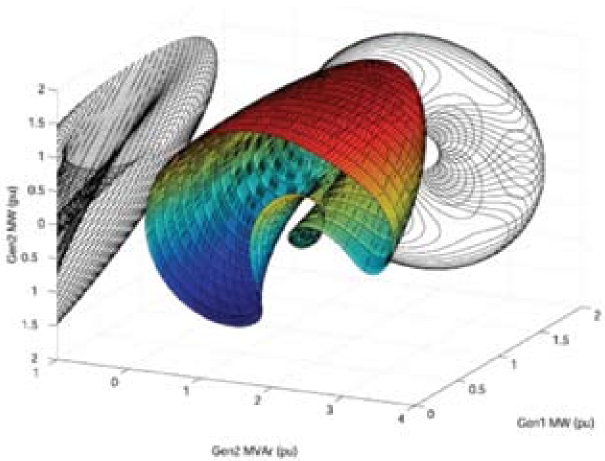
Smart grids are forcing the evolution of grid operational strategies. The variability inherent in large-scale renewable generation challenges existing regulation approaches. Plug-in electric vehicles, if adopted in large numbers, will introduce charging loads that must be carefully coordinated to avoid disruptive peaks in demand. Power transfers are continually increasing, without commensurate expansion of the underlying transmission network, forcing system operation closer to limits. To meet these operational challenges, the grid must become more responsive.

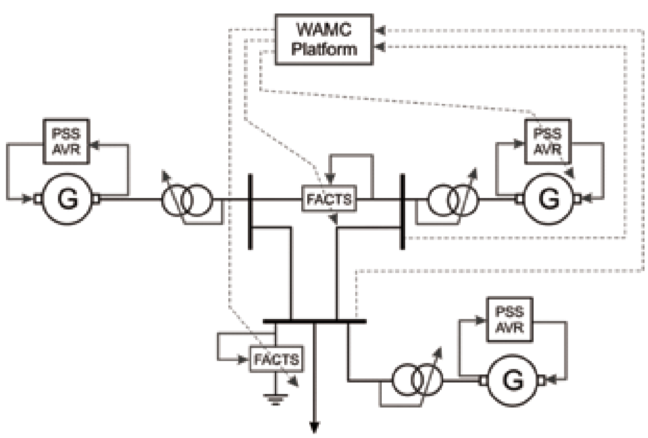
Enhanced grid responsiveness will rely on a range of available and emerging technologies. Phasor measurement units (PMUs) provide fast, accurate, time-stamped measurements that facilitate wide-area monitoring and control. Flexible AC transmission system (FACTS) devices use power electronics to control active and reactive power flows. Load control must be used for grid regulation as well. In all cases, control science and engineering will play a fundamental role in achieving stable, optimal operation.

Wide Area Monitoring and Control (WAMC)

Phasor measurement units (PMUs) provide geographically dispersed sensors that can supplement local measurements used by controllable devices, such as generators and FACTS installations. The wider view of system behavior offered by PMUs provides valuable information in determining optimal responses to system-wide events. Possibilities range from enhanced damping of inter-area oscillations to power flow modulation following large disturbances. In order to realize these benefits, however, controller designs must take into account signal latency and reliability.

PMU networks will produce copious amounts of data. Sophisticated algorithms will be required to extract information that is, 1) valuable for alerting operators to system vulnerabilities, and 2) suited to closed-loop control applications. Security of communications networks is paramount, as PMUs are often tightly integrated into substation protection schemes.





For the example power system on the right, The colored figure shows the boundary of the power flow solution space for all combinations of the active power of one generator and the active and reactive power of a second generator. (The third generator is the "slack" generator, which balances the total supply with demand.) The black-and-white figures are projections of the colored figure onto axis pairs. The figure highlights the complexity that arises from the nonlinear nature of power systems, and that cannot be avoided in real-world analysis and control applications. (AVR: automatic voltage regulation; PSS: power system stabilizer)

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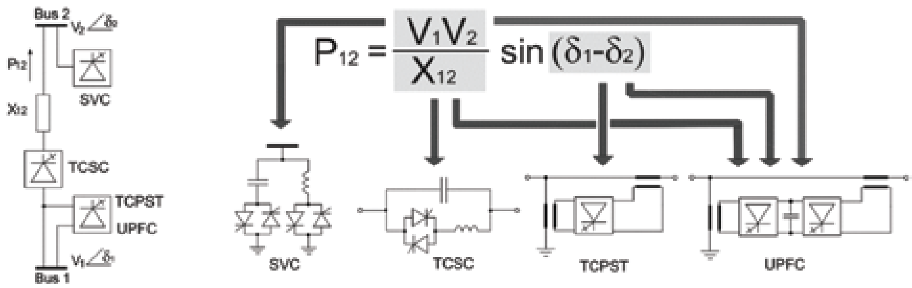
Flexible AC Transmission Systems (FACTS)

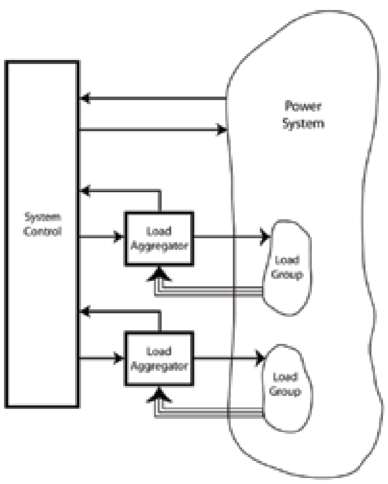
FACTS devices use the switching capability of power electronics to control voltages and currents in an AC grid. The most common FACTS devices are used to regulate bus voltages, for example at the collector bus of a wind farm. FACTS devices are, however, also capable of controlling power flow over transmission lines. Without control, power will flow through an AC network in accordance with Kirchhoff's laws. This may overload some lines, while leaving others underutilized. FACTS devices can redirect power to achieve more effective loading patterns.

Examples of FACTS devices include static var compensators (SVCs, for regulating voltage magnitudes), thyristor controlled series capacitors (TCSCs, effective line impedances), thyristor controlled phase shifting transformers (TCPSTs, phase angle differences), and unified power flow controllers (UPFCs, all of the above).

Optimal siting and sizing of FACTS schemes and their cost/benefit analyses involve nonconvex, nonlinear, mixed-integer optimization problems. Coordinated control of multiple FACTS devices must take into account the complexities inherent in regulation of a large geographically distributed nonlinear system.



Various FACTS devices



A hierarchical control structure for integrating load control into power system operation

Load Control

Power system operation has traditionally relied upon generation to balance supply and demand. However, because of the variability inherent in renewable energy production, that control philosophy will no longer be sufficient as renewable generation grows. It will become crucial for loads to participate in the regulation process.

To do so will require coordinated control of huge numbers of autonomous devices. Centralized control seems impractical, with hierarchical control structures more likely to succeed. Many outstanding control questions remain to be addressed.

Uncertainty in Power System Dynamics

Parameters associated with key power system models, in particular loads and renewable generation, can never be known precisely. To ensure robust dynamic performance, controller designs must take into account plausible parameter ranges and system conditions. This is challenging, due to the nonlinear, nonsmooth, large-scale nature of power systems.

Much work remains in the development of analytical results and numerical techniques that are suited to the analysis and design of large-scale power systems.

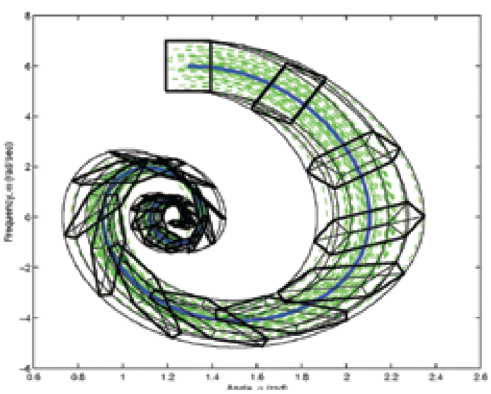


Illustration of phase angle (horizontal axis) and frequency (vertical axis) evolution in a power system showing nonlinear effects of parameter uncertainty. The complete uncertainty set generates a time-varying parallelotope that is mapped along with the nominal trajectory (the blue curve).