

Cyber-Physical Systems Distributed Control: The Advanced Electric Power Grid*

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I. INTRODUCTION

Advanced power electronics, such as Unified Power Flow Controller (UPFC) style Flexible AC Transmission System (FACTS) devices [1], when combined with embedded networked computation, allow SCADA systems to move beyond centralized monitoring to active, distributed, control of the power grid. The power grid, power electronics, and embedded control software form a Cyber-Physical-System (CPS), whose design is heavily influenced by fault tolerance, security, decentralized control, and economic/ethical social aspects. The envisioned *advanced electric power grid* **Error! Reference source not found.** provides a rich environment for the study of several inherent problems. First, these systems form one of the largest and most complexly interconnected networks ever built, and their scale makes controlling them extremely difficult. Recent federal mandates for deregulation further increase the difficulty of control. Heavier power transfers resulting from independent ownership and potentially widespread use of distributed energy generation will make power systems increasingly vulnerable to cascading failures in which a small series of events can lead to a major blackout. The envisioned advanced electric power grid must include support for decentralized energy generation and transmission controllers, whose local actions can be coordinated across multiple time scales (long term (minutes to hours), dynamic (milliseconds to seconds), and local control (microseconds) for integrated and efficient control of the power grid as a whole.

II. CRITICAL RESEARCH CHALLENGES

Three critical research challenges that must be addressed are:

1. MODELING AND SEMANTIC INTEGRATION

Crucially, modeling hardware or software elements in isolation, without reference to other design domains, ignores important interactions between them and thus risks over-constraining or under-constraining their design. Development of accurate and usable formal models of the physical

power grid and its supporting cyber-infrastructure, together with integration of hardware/software semantics (e.g., through *co-design*), are thus important research challenges. In order to obtain models, the design, verification, and validation of the actual system, techniques and educational processes are required that (1) uncover the semantic mismatches that exist between application requirements, system software behavior, economics, ethics, resource management precision, and behavioral information collected about the system, (2) uncover the semantic inconsistencies that exist between requirements, design specification, hardware/software/physical implementation, and other system artifacts, and (3) thus, make modeling, co-analysis, and co-design possible.

2. REAL-TIME CONTROL

Examples of approaches to *long term control* include distributed algorithms, agent frameworks, and/or optimization problem solutions. *Dynamic control* assumes a particular model of the power transmission system dynamics and controls its frequency response; coordination in time is crucial: for example, two FACTS devices can compete, in effect causing the controlled system to “ring.”

Important open research problems in the area of real-time control for the advanced electric power grid include: (1) effects of different communication and computation delays on both long-term and dynamic control properties (both physical *and* cyber), (2) co-design of control and monitoring feedback loops, and (3) formal models of the timing behavior of power grid control, monitoring, and actuation elements in conjunction with the timing behavior of system software elements **Error! Reference source not found.**

*Our prior work described in this paper was supported in part by NSF MRI award CNS-0420869 (UMR), CSR award CCF-0614633 (UMR/WUSTL/KU), CAREER award CCF-0448562 (WUSTL), and EHS award CCR-0311599 (KU); by DOE/Sandia (UMR); and by DARPA through PCES contract F33615-03-4111 (WUSTL and KU)

3. FAULT TOLERANCE AND SECURITY

The system's safety, liveness, fault tolerance, information security, and design and implementation robustness, are critical to power grid control [1]. In addition to the assurances of timing and information flow, robust power grid management approaches therefore must also provide security from interference, both in the cyber domain consisting of the embedded computers and communication networks, and in the physical domain consisting of the power system itself.

Important open research problems in the area of fault tolerance and security for the advanced electric power grid include eliciting application-specific constraints and security policies for both the cyber and physical domains through co-analysis that can be used to develop and enforce appropriate fault tolerance and security interlocks between interacting system components, identifying implicit (covert) interaction channels in real-world power grids, developing a common scheduling framework for all OS, middleware, and physical components immune to computational and communication interference, and reduce the complexity of verification and validation.

III. IT RESEARCH NEEDS

Sustained cross-disciplinary investigation that integrates a range of topics from computer science, power engineering, control theory, and other disciplines, forms the combined field of study: *Power Informatics*. While addressing the open research problems we have described for the advanced electric power grid will promote better understanding of those engineering domains, additional research will be needed to solve new problems posed by those other cross-disciplinary fields of study. Activities critical to addressing the challenges described in this paper include:

1. development of curricula that are collaborative and cross-disciplinary,
2. establishment of methods, such as hierarchical modeling and design, to promote modelability and to abstract portions of CPS to ease co-design and verification, and
3. development of methods to establish, analyze, and enforce operational, behavioral, and security properties of CPS more easily.

IV. ROADMAP FOR THE NEXT 5-10 YEARS

1. As a five year milestone, integrated cross-disciplinary research and educational programs should be developed that span traditional science/engineering and behavioral sciences to produce graduates capable of engineering advanced CPS. This will require investment in new educational directions as well as in integrated laboratory facilities.
2. As a ten year milestone, the demonstration of integrated CPS which are specifiable, assured, and verifiable, is a significant and worthy challenge.

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