Secure and Plug-n-Play Energy Cyber-Physical Systems

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Abstract

In this position paper, cooperative control of distributed renewable generation is outlined, and three fundamental research topics are presented for robust, intelligent and efficient operations of power systems. The first topic deals with modular design and plug-n-play operation of hetergeneous systems in such networked settings as distributed energy resources (DERs) and electric distribution networks. The second topic addresses secure cyber-physical systems by analyzing the topological and design requirements under which networked operation of cooperative systems becomes robust under attacks. And the third subject deals with game theoretical analysis and design of energy cyber-physical systems.

1 Cooperative Control of Distributed Power Generation

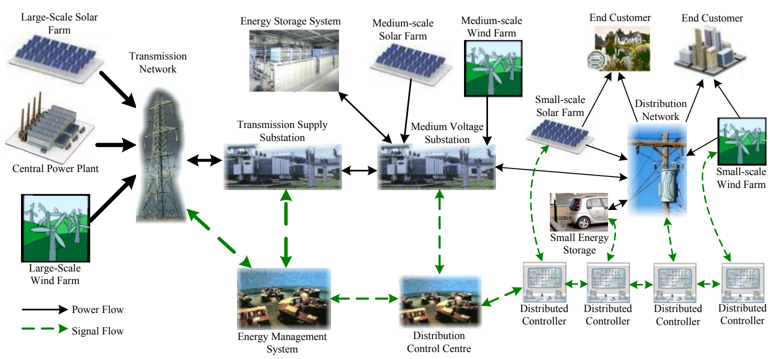

Fig. 1: A modern power grid of high DG penetration

Figure 1 shows a modern grid in which several DERs competitively and collaboratively provide power to both local loads in the microgrids and the main grid. It is well recognized [3] that these distributed energy sources are intermittent, that their presence will shift the operation of power system from the current mode of regulated utilities to a competitive generation provision, and that a high penetration level of DERs demands new regimes of communication, control, optimization, and security. Based on the dynamic energy control protocols (DECPs) [2], innovative algorithms of cooperative control, robustification, and dynamic game can be implemented to enable robust, intelligent and efficient operations for power systems with distributed and intermittent power generation sources.

Cooperative control is to make individual but networked dynamical systems achieve the same behavior (i.e., consensus) in the presence of intermittent information exchanges and/or topological connectivity changes [8]. Cooperative control problems arise naturally from energy cyber-physical systems. For instance, the voltage control problem is to ensure that the per-unit values of voltages at all the nodes in a microgid be 1 or very close to 1. For DERs to supply active power to the loads in a microgrid, the load sharing policy intuitively imposes the so-called fair utilization ratio:

$$\frac{P_i}{P_i^{\max}} \rightarrow \alpha_p, \quad \forall i,$$

that is, utilization percentages of all the DERs approach the same value. Similarly, the fair utilization ratio could be required for inverter-based DERs to compensate for reactive power, for demand response of adjustable loads, etc. Accordingly, cooperative control can be used as the underlying methodology to make micro-grid operations self-organizing, autonomous and robust. To this end, three fundamental research topics are described in the subsequent sections.

2 Modular Design and Plug-n-Play Operation of Networked Systems

For inverter-based DERs described by simple dynamic equations, cooperative control has been shown in [13] to be very effective for both dispatch of active power as well as reactive power compensation. In general, the dynamics of both DERs and adjustable loads can be quite distinct from one to another. To characterize input-output relationship of such heterogeneous devices and to enable plug-n-play of their networked operation, we can use the concept of passivity: The ith dynamic system of $\dot{z}_i = f(z_i, u_i)$ is said to be *dissipative* if, for a storage function $V_i(z_i)$ and a supply rate $\Phi_i(z_i, u_i)$, the following inequality holds:

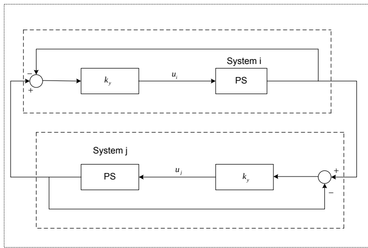

Fig. 2: Networked operation of two PS systems

$$V_i(z_i(t)) - V_i(z_i(0)) \leq \int_0^t \Phi_i(z_i(\tau), u_i(\tau))d\tau.$$

The system is said to be *input feedforward passive* or simply *passive* if, for some positive semi-definite function $\eta_i(\cdot)$ and for some $\epsilon_i \geq 0$,

$$\Phi_i(z_i, u_i) = -\eta_i(z_i) + u_i^T y_i + \frac{\epsilon_i}{2}\|u_i\|^2.$$

If $\epsilon_i \geq 0$ in the above definition, the system is said to be *passivity-short* (PS), and ϵ_i is referred to as the *impact coefficient*. It is apparent that passivity-short (PS) systems include passive systems as a special case of $\epsilon_i = 0$. It is shown in [12, 9] that controllable linear and nonlinear systems can individually be stabilized into PS systems and that, as illustrated by figure 2, PS systems are plug-n-play under cooperative control laws. This modular design methodology and local distributed implementation are well suited for applications to energy cyber-physical systems, and on-going research focuses upon some of these applications.

3 Secure Cooperative Systems Against Attacks

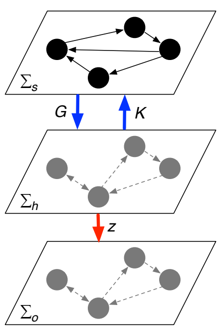

Fig. 3: A design of secure cooperative systems

Cooperative control is specifically geared toward networked systems and requires only local information, but its dispersed implementation makes the cooperative system susceptive to attacks by malicious agents. It can be shown using counterexample that, unless all the dynamic systems are passive, cooperative systems could be destabilized by data attacking involving simply linear dynamics. It is shown in [1] that this vulnerability can be overcome by introducing competitive stabilization and desired robustification can be achieved by using the three-layer design shown in figure 3. Specifically, networked system nodes and their distributed cooperative control are denoted by Σ_s of Laplacian L_s, a hidden network denoted by Σ_h of Laplacian L_h is then designed to achieve robustification of the overall network system through competitive stabilization, and finally an observation network of Σ_o can be employed to identify potential attackers. Fundamental research is being carried out to develop the relationship among Σ_s, Σ_h and Σ_o for design and performance guarantee.

4 Game Theoretical Algorithms for Energy Cyber-Physical Systems

As has been shown in [11, 5], distributed optimization and game algorithms are instrumental to enable formation of self-evolving micro-grids and their intelligent and reliable operations and to make DERs and loads respond to the incentive or stability demands of the main grid. Recent research efforts focused upon development of distributed game strategies, both cooperative algorithms [10, 6, 7], and noncooperative strategies [4]. We plan to apply these algorithms to smart distribution networks and also investigate game-theoretical designs of secure cyber-physical systems.

Through the workshop, we hope to exchange ideas and collaborate toward developing systematic methodologies for analyzing, designing and operating energy cyber-physical systems.

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