Emerging Research Topics in Control for a Smart Infrastructure[☆]

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Abstract

As we move deeper into the 21st century, critical infrastructures related to energy and transportation are becoming smart - monitor themselves, communicate, and most importantly self-govern. Various drivers have enabled this transition, including sustainability concerns, scarcity in resources, economic considerations, and rapid growth in enabling technologies of sensor networks, and computational and communication systems. Two notable examples of such infrastructures are smart grid and smart cities. The idea behind a Smart Grid is the creation of a dynamic, cyber-physical infrastructure that meets the challenges of intermittency and distributed availability of renewables, and realizes reduced operational costs and emissions, via a flexible, intelligent, and networked grid that plans, controls, and balances supply and demand over an entire region. The concept of a Smart City is gaining popular attention driven by goals of sustainability and efficiency, the needs of enhancing quality of life and affordability, growing urbanization of the world's population, and the explosion of technological advances in communication and computation. While systems and control problems abound in any complex dynamic system, two characteristics that are specific to critical infrastructures are the need to deliver reliable service and the ability to accomplish this goal amidst constrained

[☆]This work was supported in part by the National Science Foundation grants ECCS-1135815 and EFRI-1441301.

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resources. These in turn lead to new research topics in systems and control including empowered consumers, transactive control, and resilience. The focus of this paper is on these emerging topics. Their role in smart infrastructures, the opportunities they provide, and the research challenges that they bring in are all discussed. Specific illustrations of recent successes are presented that are based on coordinated adjustment of generation and consumption using concepts of multi-agents and multi-timescales in smart grids and socio-technical models of empowered drivers in smart cities.

Keywords: Smart Grids, Smart Cities, Empowered Consumers, Transactive Control, Resilience, Multi-timescales, Multi-agents, Control, Stability.

1. Introduction

The field of control theory and technology pertains to the governance of complex dynamic systems. Enabled in large measures by the drive towards automation, control theory has evolved with the goals of command following and disturbance rejection through on-line measurements of the underlying system. Such information-based decision making has, over the past decades, led to tremendous advances in a wide variety of engineering systems including aerospace, automotive, robotics, process control, and medical devices. The overarching concept that has pervaded the analysis and synthesis of control systems in these applications is decision making using information gathered by these systems, both from physics-based models and on-line measurements. With theoretical advances taking place in control systems, and accompanying advances in sensing and actuation technologies, it can be argued that we have obtained a good understanding, at a systems level, of basic properties of stability, robustness, and reliability. With recent theoretical advances in hybrid, switched, and event-triggered systems, and accompanying advances in real-time and embedded systems, basic properties of networked control systems are well understood as well. With some of the above underpinnings, it can be argued that attention is shifting towards the design of large and smart infrastructures and the

fundamental principles of control therein.

Infrastructures are the basic physical and organizational structures and facilities (e.g., buildings, roads, and power supplies) needed for the operation of a society or enterprise. Infrastructures have been around as long as urban centers, supporting a society's needs for its planning, operation, and safety. As we move deeper into the 21st century, these infrastructures are becoming smart, through sensors of various kinds that provide information about the infrastructure as well as decision-makers that effect a change in the infrastructure, and help provide a service of value to the end-user that's infrastructure wide. This service needs to be provided reliably, economically, and in a resilient manner. Examples are the delivery of reliable and affordable power, water at a high quality, or transportation at an affordable cost.

Information-based decision-making is a necessary ingredient in any complex system. As systems become more intricate with increasingly stringent performance specifications, there is a need for sensors and actuators to be ubiquitous for the purposes of gathering information about the system behavior and its management. As systems increase in scope and size, incorporation and integration of a communication network is mandatory. Associated with this integration is the need for any information gathering or decision-making to occur using coordinated, cooperative, and distributed yet optimal control. And concomitantly present are myriad uncertainties in modeling the system behavior, a host of environmental disturbances, time-variations, and nonlinearities. Given that any smart infrastructure is first and foremost a large and complex system, all of the aforementioned features including uncertainties, nonlinearities, and other disturbances, and the need for pervasive sensors and actuators as well as coordinated, cooperative, and distributed control optimization are also common to and essential for the design of a smart infrastructure. There are, however, two distinguishing aspects to a smart infrastructure that are noteworthy. The first is that the central goal of an infrastructure is to deliver a critical service, such as energy, food, water, healthcare, or transportation. The criticality implies that in addition to meeting the desired performance under nominal times,

it is extremely important to deliver essential service in the event of emergencies. This in turn implies that a smart infrastructure should be designed so as to accommodate both normal and emergent situations. The second aspect of an infrastructure is the availability of constrained resources. Whether energy, water, transportation or healthcare, the available resources are limited. As a result, optimal use of resources even as operating constraints increase is mandatory. Given that notion of a *smart* system is one that accomplishes more by using less [1], a smart infrastructure therefore needs to accomplish its objectives even with limited resources and increasing number of constraints.

The thesis of this paper is that the above two features of a smart infrastructure lead to the following three emerging research topics in control: Empowered Consumers, Transactive Control, and Resilient Control. The first topic addresses the fact that resources are constrained and therefore active decision making in managing consumption. The second addresses the opportunity provided by the first topic which enables several *actuators* and provides an architecture for coordinating their actions and enabling global optimization using local outcomes related to financial transactions. The third is a direct consequence of the need to address the two objectives of a smart infrastructure, of satisfactory behavior in the nominal case and at the same time resilient performance in the face of emergencies.

The first of these emerging topics concerns the consumer, to whom the underlying infrastructure has to provide a service. In contrast to the traditional role of the consumer, which is typically a passive one, the consumer in a smart infrastructure is more central, and notably an active one. Given that the major problem in a smart infrastructure is one of managing resources and making them available at the right location and at the right time, there is a distinct paradigm shift taking place in this topic. The end-user is empowered with making decisions, based on frequent, real-time, and distributed information available about the overall infrastructure. The questions that arise related to such a decision making as well as the collection of pertinent information and its processing, the requisite tools, methodologies, and challenges are all problems that fall within

the broad rubric of systems and control.

If one can view the first topic of empowered consumers as an actuator, Transactive Control, the second emerging research topic in a smart infrastructure, can be viewed as a control input to this actuator. Given that in a smart infrastructure, the consumer plays an active role and can carry out decisions that impact the infrastructure dynamics, the question that arises is about the actual signal that the consumer responds to. Defined broadly as a mechanism through which system and component-level decisions are made through economic transactions negotiated between the components of the system [2], Transactive Control is now being explored in depth in the context of a smart grid infrastructure, and is beginning to be explored in the context of smart cities as well [3]. Given that transactive control provides an opportunity for designing a closed-loop, the specific feedback mechanism of the underlying transactions needs to be suitably designed, and accommodate both the behavioral model of the consumers and economic objectives of the infrastructure. A plethora of challenges remains to be addressed, as a result, pertaining to cooperation and coordination of multiple consumers and organizations, constraints on all entities that are involved in the underlying transactions, and dynamic modeling and accommodation of multiple time-scales associated with the problem.

The third topic is resilience of the infrastructure. A distinguishing feature of any infrastructure is not only its ability to deliver a service, but to deliver it in a reliable and resilient manner. The former can be argued as a robustness property under nominal disturbances. Resilience refers the capacity of an infrastructure to recover from setbacks, adapt well to change, and continue to operate in the face of adversity [4], that is, its ability to withstand severe disturbances, both random failures and targeted adversarial attacks, and still continue to function. In the presence of empowered users, who can directly impact the control actions within the system, it is critical to engineer resilience into the infrastructure. However, the tight coupling of the continuous and the discrete dynamics in a smart infrastructure make the design and analysis of a resilient controller particularly challenging. An obvious challenge arises from the scale of

the infrastructure; while each individual system may have a small state space, the coupling between these systems leads to a very large number of interacting states. Additionally, the faults and attacks in one part of the infrastructure can propagate to adversely affect other systems. A more subtle challenge is balancing the diverse requirements and constraints of the composite system. The optimal control strategy for an individual system may not align with the global requirements leading to compromises.

A Smart Grid is an end-to-end cyber-enabled electric power system, from fuel source, to generation, transmission, distribution, and end use, that has the potential to (i) enable integration of intermittent renewable energy sources and help decarbonize power systems, (ii) allow reliable and secure two-way power and information flows, (iii) enable energy efficiency, effective demand management, and customer choice, and (iv) provide self-healing and resiliency not only from physical anomalies but also cyber-attacks. The need for such a change is precipitated by the need for reducing greenhouse gas emissions, staggering growth in energy demand and aging electricity infrastructure.

One of the most promising concepts that is being explored to realize the smart grid vision is Demand Response (DR), a concept which allows demand to be adjustable [5, 6, 7], to cope with variations in RERs. A fairly vast literature exists on Demand Response, its potential, and associated challenges and opportunities [8, 9, 10]. The concept of introducing flexible consumption in grid planning and operations has long been recognized as a highly beneficial one [11, 12]. The idea is then to determine the procedure by which DR can be used concomitantly with renewable resources so as to ensure an optimal economic dispatch of generation for power balance.

The above discussions clearly illustrate that energy resources available are limited. While renewables provide opportunities for clean energy with minimal generation cost, they introduce a significant amount of intermittencies and uncertainties. Empowering consumers provides one opportunity for addressing these challenges. Incentivizing these consumers in a suitable manner to shift or adjust their consumption is yet another opportunity. Given the criticality of

energy delivery, a resilient grid performance is a must. The challenge then is how control can be used to gather any and all information that available about the grid, facilitate a resilient functioning of transmission and distribution networks, shape any and all loads that are responsive, and allocate all dispatchable generators, storage, and electric vehicles to deliver a smart grid infrastructure. In this paper, we provide some examples of a smart grid, using a modified IEEE 118-bus system, which illustrates the roles of empowered consumers, transactive control, and resilient control.

The concept of Smart City is gaining popular attention with the goals of sustainability, efficiency, and resiliency, the needs of enhancing quality and performance, and the explosion of technological advances in communication and computation. Given that 50% of the world's population lives in urban regions [13], critical infrastructures of energy, transportation, and health and their growing interdependencies have to be collectively analyzed and designed to provide the substrate for the realization of the Smart City Concept. Solutions for achieving all three goals are based on smart decision making using various kinds of information resources, i.e. feedback control. Several problems are emerging in the above critical infrastructures in relation to smart city, in the areas of transportation, water, and electricity [3]. While specific illustrations of the aforementioned three topics are yet to emerge in the context of smart cities, that all of them play an important role, just as in Smart Grids, is easy to see. Empowered consumers can clearly make decisions regarding consumption of any resource including highway travel, parking, water, electricity, or gas. Transactive control can be a means for these consumers to gain maximum benefit, since it can enable them to make decisions that optimize their utility functions and global objectives. Among the several key functionalities that a Smart City needs to provide, an essential one is for the overall smart city infrastructure to perform resiliently in the face of physical and cyber anomalies. This paper focuses on a specific example that occurs in the context of transportation in a smart city, especially highway congestion, and will underscore the role of empowered consumers and transactive control.

In the following sections, each of the above three research topics will be discussed, with emphasis on their roles in the above examples of smart grids and smart cities. Connections between the underlying problems and the possible solutions that control systems can provide will be discussed in all sections as well.

2. Empowered Consumers

The traditional role played by consumers in infrastructures is a passive one. Whether it's electricity consumption in power grids, water consumption, or transportation resources such as parking and highway occupancy, the current practice has been that demand remains inelastic [14]. In power grids, for instance, customers consumed as much power as they wanted, whenever they wanted it, and accepted a feedback mechanism in terms of an electricity bill with a time delay that's typically a month's duration. The infrastructure is then designed by adjusting resources and associated components so that supply of resources exceeds demand. Of late, this notion is being challenged, with Demand Response, a concept that connotes flexible consumption.

Demand response denotes the concept of adjustable demand in response to grid conditions and incentives and has a history dating back at least to Fred Schweppe's pioneering work on homeostatic grid control in the 1970s [15]. His work pertained to the economic principles of supply-demand control through an energy marketplace using time-varying spot prices [16, 17]. By allowing consumption to be adjusted alongside of generation, the premise is that one can manage uncertain and variable renewable generation in a much more efficient manner. That is, by using a judicious control algorithm that simultaneously adjusts the demand as well as generation, the goal is to deliver reliable and affordable power. This concept is now beginning to be explored in other infrastructures such as highway transportation, parking in urban centers, water networks, and natural gas networks.

The biggest challenge that the empowerment of consumers introduces is the

fact that there are multiple decision makers. In addition to the fact that there are several “actuators”, capable of introducing independent control inputs, the additional complexity is that these end-users are of different kinds. In the context of a smart building, in addition to the occupants, users include management, maintenance staff, and grid-side operators, to name a few. In the context of power grids, in addition to individual consumer, there are microgrid operators, utilities, regulation agencies, and several other balancing authorities [18]. The question then is how global performance specifications (such as frequency control and power balance in a power grid) related to reliability and affordability that are central to infrastructure needs can be achieved with multitudinous agents exercising their options and decisions at multiple time-scales.

2.1. Dynamic Models of End-Users

Given that consumers can allow demand to be a flexible entity, the next step is to model the value function that the consumers are most responsive to. In the context of smart grids, for example, the underlying model may have a structure as in Fig. 1, where the first block returns a risk aversion function that may be dependent on economics, environment, comfort, or other factors. This decision then becomes an input into a physical system, such as HVAC, Refrigerators, or other entities. Such models have begun to be employed both in the context of smart grids [19] and smart cities [20]. We briefly explain the example in [20] that shows the role of end-users.

Figure 1: Dynamic Models of Consumers

With the growth and expansion of many large metropolitan centers in the last few decades, the problem of traffic congestion continues to grow and vex commuters, commercial drivers, city planners and officials, and environmentalists worldwide. Over 1 billion vehicles travel on the roads today, and that number is projected to double by 2020 [13]. Driving a car is an unavoidable choice for at least 65% of city populations, who rely on their vehicles to get to school or to work [21]. In [20], a novel approach of determining dynamic toll pricing for alleviating traffic congestion is proposed so that traffic flow can be increased during peak hours of the day. The approach in [20] develops an overall model that is socio-technical in nature, and is shown in Fig. 2. This is derived using a combination of traffic flow dynamics cascaded with the behavioral dynamics of a driver.

Figure 2: A socio-technical model of traffic flow in the presence of empowered drivers

Figure 3: The similarity of the density and speed plots of our simulated system (blue) and the actual MnPASS system (red) validate the use of our model-based system.

The rationale behind such a model is as follows: The dynamic toll-price is observed by the driver who can be viewed as an actuator - by virtue of his or her

decision to enter the HOT lane, the driver affects the traffic flow. This in turn modifies the boundary condition of a traffic model, which is captured in the form of the model structure in Fig. 2. The model structure together with suitably chosen parameters was validated using MnPass, one of the earliest dynamic toll pricing system in the US [22], the results of which are shown in Fig. 3. It was also shown in [20] that a model-based toll-pricing controller, that consists of a nonlinear PID structure, can be designed and result in an improved total traffic flow while staying under a specified maximum toll-price. This demonstrates the feasibility of determining such socio-technical models that accommodates the behavior of empowered end-users in an infrastructure.

3. Transactive Control

A concept that is eliciting significant attention of late is Transactive Control [2, 23, 24], a feedback control strategy enabled through economic contracts to incentivize and enable flexible consumption. A typical transactive controller consists of an incentive signal sent to the consumer from the infrastructure and a feedback signal received from the consumer, and together the goal is to ensure that the underlying resources are optimally utilized. This implies that the overall process introduces a feedback loop, where empowered consumers serve as actuators into an infrastructure, and Transactive Control represents a feedback control design that ensures that the goals of the infrastructure are realized (see Fig. 4).

Figure 4: The role of transactive control in a Smart Infrastructure. A mechanism through which system- and component-level decisions are made through economic transactions between the components of the system, in conjunction with or in lieu of traditional controls.

The idea of Transactive Control can be traced to Homeostatic Control proposed in [16, 17], which suggested that demand-side assets can be engaged using economic signals. Although technologies for effective demand-side management did not exist then, it's clear that the concept is essentially a precursor to the currently popular DR one.

Given the obvious connection between transactive control and the DR-concept prevalent in smart grids, we elaborate further on DR techniques that are currently in use. DR techniques can be classified into three categories: 1) incentive-based, 2) price-based, and 3) transaction-based. In incentive-based DR programs (known as direct load control (DLC)), utilities, local grid operator, or load serving entities offer a contract to remotely shut down or cycle air conditioner, water heater or other customers electrical appliances [25, 26]. In return, customers receive a rate discount for the agreement. Although there is more certainty about the amount of load to be curtailed or shifted, DLC requires an expensive infrastructure for direct communication with individual appliances or loads, and in addition, customers privacy and preferences are not respected [27]. In price-based DR [28, 29] the customer changes the demand in response to changes in the electricity price and includes tariff categories such as time-of-use (TOU), real-time pricing (RTP), and critical-peak pricing (CPP). In TOU customers are charged based on different unit prices for usage during different blocks of time. In RTP day-ahead or hour-ahead variations in wholesale electricity prices are reflected in retail electricity prices and customers are notified and charged accordingly. CPP is the combination of TOU and RTP in which TOU serves as the basic rate structure while normal peak prices in RTP are replaced with much higher ones to reflect specific situations such as periods with very high supply price conditions or when system reliability is compromised. Although it is simple and easy to deploy, price-based DR is challenging from the view of predictability since customers load adjustment is entirely voluntary. Such an open loop indirect control over customers may cause power volatility especially in large-scale price-based DR programs [30, 31].

Transaction-based DR [32, 33, 34, 35], which coincides with Transactive

Control for smart grids, is a market-based control mechanism that incentivizes responsive loads and engages them in providing services to the grid where and when of great need. The set of prices and desired consumption to be exchanged with the utility are respected as sensitive customer information, so the privacy and preference of the customers will be respected. Moreover, Transaction-based DR has the ability to close the loop by integrating customers via the right incentives to meet their local objectives such as lowering their electric bill as well as meeting global system objectives such as voltage and frequency regulation. While transaction-based DR may require slower time-scales relative to DLC for its implementation, it may allow a wider participation by enabling consumers to exercise their autonomy.

Over the last decade, there have been field projects demonstrating the idea of Transactive control [36, 37, 38, 39, 40]. In the U.S., Olympic Peninsula GridWise Project was the first attempt to demonstrate the ability of Transactive control to engage market-driven load and generation resources for power-grid management [36]. While in real-time contracts for retail electricity sales, responses to price intervals were about 15 minutes in a one-way transaction, Transactive control has been demonstrated to reduce the clearing time of process to intervals as short as 5 minutes using feedback demand bids. AEP Ohio gridSMART demonstration project [37] was the second dynamic pricing demonstration analysis involving four feeders with approximately 200 households. The project outcome has led to an experimental retail tariff approved by the Ohio Public Utility Commission. The Pacific Northwest Smart Grid Demonstration (PNWSGD) [38] was one of the largest and most comprehensive demonstrations of electricity grid modernization ever completed. The demonstration deployed a transactive system to coordinate the operation of distributed energy resources (DERs) and addressed regional objectives, including the mitigation of renewable energy intermittency and the flattening of system load [41]. The transactive system coordinated a regional response across 11 utilities and showed that distributed assets can respond dynamically on a large scale. Within the European electricity sector, Power-Matcher [39] was the major transaction-based mechanism installed to integrate

numerous households, industrial sites, and prosumers and coordinate them for trading activity. The ability of PowerMatcher was tested in the field projects such as Couperus Smart Grid demonstration [40] in Netherlands where heat pumps from 288 apartments in a tower were used to reduce imbalance caused by wind energy integration as well as peak shaving on the local low-to-medium voltage substation.

The above discussions show that the concept of Transactive Control as discussed above, shown schematically in Fig. 4, has a strong potential in realizing the goals of a smart grid. While application of Transactive Control, together with Empowered Consumers lead to closed-loop control, it can also be challenging. First, although multi-agents who can make autonomous decisions are present, they have to be properly coordinated for robust and optimal performance. Second, global objectives have to be realized using local actions and distributed architectures. Third, multiple time-scales are present, with the faster ones related to operations and the slower ones on planning. As such, the underlying tools for the analysis and design of Transactive Control have to be assembled not only from systems and control theory and include behavioral models of individuals, consumers, and organizations, but also theory of microeconomics such as mechanism design, theory of incentives, game theory, and contract theory. In addition to assembling the underlying theoretical results and understanding the fundamental challenges in the analysis and design of market-based control, one also needs to identify potential barriers for the adoption of these control strategies and consumers gaming the system, as their implementation will have to be approved by entities related to policy and regulation, and accommodate strategic and non-rational consumer behavior.

In what follows, we focus on two aspects of Transactive Control, its multi-agent system structure and its multi-timescale dynamic evolution. The first concerns the presence of multiple agents who need to coordinate, cooperate, and make decisions based on local information so that global outcomes at an infrastructure level are realized. The second concerns decision making in the presence of multiple time-scales and a hierarchical and heterogeneous architec-

ture. Examples from Smart Grid will be used to illustrate these concepts and their role in the analysis and synthesis of Smart Infrastructures.

3.1. Multi agents

Two major drivers for pursuing a paradigm shift in power grids are the need for increased use of renewable resources such as solar and wind for power generation and the use of flexible consumption from devices such as HVAC, pluggable electric vehicles (PEV), and other thermostatic loads. The typical procedure used to achieve power balance is to determine the schedules of generation and consumption over a certain period such that an underlying cost function is optimized [42]. This cost function, denoted as Social Welfare, represents the difference between utility gained by the consumers and the cost incurred by the generators over the period of interest, and is of the form

$$S_W(x, y) = U(x) - C(y) \quad (1)$$

where x and y denote consumption and generation respectively, $U(\cdot)$ denotes the utility function of consumers, and $C(\cdot)$ denotes the cost function of generators. This cost needs to be optimized under a variety of constraints including ensuring power balance, and meeting capacity and ramp limits. These include equality constraints of the form

$$g_1(x, y, z) = 0 \quad (2)$$

where z denotes external variables such as phase angles. In addition, inequality constraints of the form

$$g_2(x, y) \leq 0 \quad (3)$$

have to be simultaneously satisfied as well, where g_2 denote capacity and ramp constraints. The underlying optimization problem, denoted as Optimal Power Flow (OPF), corresponds to the maximization of S_W , given by

$$\max_{x \in \mathcal{X}, y \in \mathcal{Y}} S_W(x, y) \quad (4)$$

where $\mathcal{X}$ and $\mathcal{Y}$ denote the set of consumers and generators participating in the energy market. A preceding step to OPF, denoted as the Unit Commitment problem, typically involves the determination of the set $\mathcal{Y}$.

Due to the emerging drivers of renewable energy penetration and flexible consumption, both the equality and inequality constraints above need to be expanded to include the dynamic evolution of the available renewable energy resources and constraints on flexible consumption [43]. As outlined in [43], the type of constraints that may need to be included for flexible consumption depends on the type of demand. Grouped under the categories of Buckets, Batteries, and Bakeries, those that only have constraints on their power and energy limits, such as air-conditioning units and refrigeration systems come under the category of Buckets, those that have additional constraints on the period of consumption, such as PEVs and swimming pool circulation systems, can be categorized as Batteries, and those that require any consumption to be uninterrupted over a certain period, such as batch-processing plants are categorized as Bakeries. The point therefore is that each of these consumption devices is subject to its own set of constraints and should participate in the overall optimization of the cost function in (1). In addition to these costs and constraints, several other grid dynamics needs to be controlled, as any power imbalance can result in frequency deviation as well as voltage deviation that can have serious implications on power system stability. The question then arises as to how the multiple agents of generators and consumers can operate so that their individual constraints are respected and at the same time, they ensure that both optimization of economic costs as well as stability of the underlying dynamics are guaranteed.

One possible approach to the above problem is to recast the problem in terms of a dynamic system as follows. Using (1) - (3), one can define an augmented Lagrangian in the form of

$$\mathcal{L}(x, y, z, \lambda, \mu) = S_W f(x) + \lambda^T g_1(x, y, z) + \mu^T g_2(x, y, z) \quad (5)$$

The equilibrium point $(x^*, y^*, z^*, \lambda^*, \mu^*)$ that optimizes (5) can be arrived at

using an iterative solution such as the primal-dual interior point method given by

$$x(t+1) = x(t) - \alpha_x \nabla_x \mathcal{L}(x, y, z, \lambda, \mu) \quad (6)$$

$$y(t+1) = y(t) - \alpha_y \nabla_y \mathcal{L}(x, y, z, \lambda, \mu) \quad (7)$$

$$z(t+1) = z(t) - \alpha_z \nabla_z \mathcal{L}(x, y, z, \lambda, \mu) \quad (8)$$

$$\lambda(t+1) = \lambda(t) + \alpha_\lambda \nabla_\lambda \mathcal{L}(x, y, z, \lambda, \mu) \quad (9)$$

$$\mu(t+1) = \mu(t) + \alpha_\mu \text{Proj}_\mu (\nabla_\mu \mathcal{L}(x, y, z, \lambda, \mu), \bar{\mu}, \underline{\mu}, \epsilon) \quad (10)$$

where α_x , α_y , α_z , α_λ and α_μ are positive scalars controlling the amount of change in the gradient direction and $\text{Proj}_\mu(\cdot)$ is a projection operator that ensures non-negativity of μ_j . It can be shown this iterative solution can be written compactly as a dynamic system

$$\begin{bmatrix} x_1(K+1) \\ x_2(K+1) \end{bmatrix} = \begin{bmatrix} A_1 & A_2 \\ 0 & I \end{bmatrix} \begin{bmatrix} x_1(K) \\ x_2(K) \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2(x_1, x_2) \end{bmatrix} \quad (11)$$

where x_1 and x_2 correspond to the iterative amount and price of generation and consumption, A_1 , A_2 and b_1 correspond to the parameters of the underlying transmission topology, and b_2 represents nonlinear effects due to projecting variables to lie within their limits. The iterative solution in (11) is denoted as a Dynamic Market Mechanism (DMM) (see [43], [44]), and represents a transactive controller that seeks to minimize the global objective in (5) using the local adjustments in (11). The following theorem, derived in [43], outlines conditions under which various agents in x_1 and x_2 converge to the unique equilibrium that optimizes the Lagrangian.

Theorem: Let strong duality hold. Then the equilibrium (x_1^*, x_2^*) of (11) is stable for all initial conditions in a bounded set if A_1 is Schur-stable.

3.1.1. Validation of multi-agent iterative approach

The case studies reported below use a modified IEEE 118 Bus system, a high fidelity simulation of the Midwestern US Power Grid as of December 1962. The

Figure 5: Modified IEEE 118 Bus for Validation of the Multi-agent Iterative Approach

modified bus system consists of 54 generators, 99 consumers, and 186 transmission lines connected as shown in Fig. 5.

Of the 54 generators, 9 were assumed to be from wind power generation. All 99 consumers were assumed to be flexible. Generators and consumers are labeled as Type 1, 2, or 3, based on their power and energy capacities. Consumers are further divided into three categories, Buckets, Batteries, and Bakeries, that were described above [43]. The objective is to determine if, as the amount of wind generation changed, multi-agents can contribute a varying profile of generation and consumption using the DMM in (11) over time so that power balance is maintained. The results are shown in Fig. 6, which illustrates that generators of various types and flexible consumers of different categories and types can come together in a coordinated manner and meet the power balance requirement. It was also observed that the resulting cost was significantly improved when compared to current practice [43].

3.2. Multi-time scales

Yet another compelling component of a smart infrastructure is the presence of multiple time-scales and the management of a range of metrics in each of these time-scales. We propose that a hierarchical management of these time-scales needs to be carried out with carefully designed interconnections between

Figure 6: The behavior of the multiple agent dispatch is evaluated over 12 market clearing instances when renewable generation was assumed to drop by 30% at market clearing instance 7. Other agents participating in the dispatch included conventional generation resources as well as the BBB consumers. The latter was assumed to be of three different types, varying in their power and energy capacities as well as utility characteristics. The figure shows that the shortfall due to the RER drop is efficiently made up through the use of negative consumption in the device (ex. a Bucket).

these various layers.

In the context of power grids, typical time-scales that occur in their planning and operation are shown in Fig. 7. As is evident from the figure, most of the timescales where traditionally controls has played a part occur on the left, in the context of their operation, whereas most of the timescales related to planning occur on the right. Decisions on the right are made by electricity markets, which typically determine set-points for generators through suitable market settlements. The decisions, both on the planning and operations stages, typically occur fairly independently, with few points of coordination. However, the two major drivers, renewable generation and Demand Response, that are causing the shift towards a Smart Grid, occur at time-scales that lie in between these two stages (shown in a blue rectangle in Fig. 8). This suggests that an altogether new point of view should be taken as to how decisions need to be made, both in Planning and Operations, to address the integration of renewable energy and flexible consumption into power grids.

Figure 7: Time-scales in a Power Grid. Source: California Energy Commission California Institute for Energy and Environment May 2014.

Figure 8: Smart infrastructures with multiple time-scales

To illustrate this point of view, we assume that the interaction between the system dynamics at different time-scales is described by the nonlinear differential equations [45]

$$\varepsilon_k \dot{x}_i^{[k]} = f_{1,i}^{[k]}(x_i^{[k]}) + \sum_{j=2}^{n_k} f_{2,ij}^{[k]}(x_j^{[k]}) + \sum_{l=1}^{n_k-1} f_{3,il}^{[k-1]}(x_l^{[k-1]}) + f_{4,i}^{[k+1]}(x_1^{[k+1]}, \dots, x_{n_k+1}^{[k+1]}) + g(x^{[k]})u^{[k]} \quad (12)$$

where ε_k represents the relative timescale that the dynamics in the k th subsystem occurs at,

- $x_i^{[k]}$ represents the i th node/state in the k th subsystem;
- $f_{1,i}^{[k]}$ represents the *intra-dynamics* of the i th node of the k th subsystem;
- $f_{2,ij}^{[k]}$ represents the *inter-dynamics* of how the j th node of the k th subsystem

tem influences the i th node/state;

- $f_{3,il}^{[k-1]}$ represents the *disaggregated dynamics* of how the l th node of the upstream subsystem influences the i th node of the k th subsystem;
- $f_{4,i}^{[k+1]}$ represents the *aggregated dynamics* of how the nodes in the $(k+1)$ th downstream subsystem influence the i th node of the k th subsystem.
- $u^{[k]}$ represents exogenous influences on the entities at the k th subsystem
- $g^{[k]}$ represents the sensitivity of entities at the k th subsystem w.r.t. exogenous influences.

Given that each of these k subsystems has to meet its own performance goals of stability, robustness, and optimization, the question is how disaggregation and aggregation functions $f_{3,il}^{[k-1]}$ and $f_{4,i}^{[k+1]}$ should be properly chosen so as to meet these various goals, for a specified set of intra- and inter-dynamics. While the above discussions have been carried out using differential equations in order to illustrate the disparate timescales, a similar treatment using difference equations can also be applied, which may be more natural for infrastructures in process control.

We briefly illustrate one instance by which aggregation can be designed so as to lead to a better performance in a power grid [44]. We consider the problem of power balance in a real-time market together with frequency control which is typically termed Automatic Generation Control (AGC). Current practice is to carry out market clearing using OPF, over a 5-minute window. Any departures from these set points, which may be necessitated because of additional load disturbances, are managed through AGC Updates, that occur over a 4 second time-scale (see Fig. 9). In contrast, we proposed a faster time-scale of 30 seconds for the market clearing, with the iterations similar to those described in (11) occurring over a 4 msec period. In addition, a suitable aggregation of the power imbalance, which manifests as frequency deviation, was fed into the DMM from the AGC system, so as to better interlace the slower and faster

timescale. Conditions under which the overall multi-time scale system is stable were derived in [44].

Figure 9: Time Scales Introduced by DMM in comparison with current practice

3.2.1. Validation of the multi-time scale iterative approach

Similar to the previous example, the multi-time scale method described above was used to generate set points for generation and flexible consumption, using an algorithm similar to (11), and implemented on a modified IEEE-118 bus. The algorithm included an aggregation component fed back from the faster time-scale of AGC (see [44] for details of the algorithm). The results are shown in Fig. 10 and 11, with the set-points of the slower time-scale, and a performance metric of the faster timescale, denoted as the Area Control Error, respectively. Both plots show a satisfactory performance of the proposed method. A comparison with the current practice which is based on OPF, is shown in Fig. 11, which illustrates the improved performance that can be obtained using the proposed method. Also shown is the effect of a feedback gain introduced in the aggregation feedback.

The above example illustrates that transactive control can be carried out using multiple agents that included flexible consumers, renewables, and conventional generation resources. Multiple time-scales that are present in the system can be exploited to ensure multiple system objectives. While the above example focused on smart grids, we expect similar advantages to accrue from the multi-agents and multi-timescale methods in a smart city as well. As models

Figure 10: Setpoints of Generation and Demand using the modified multi-time scale approach

Figure 11: Area Control Error, a performance metric of the subsystem with the faster time-scale, using the modified multi-time scale approach in [44].

of critical services to a city become better informed, and the role of empowered agents becomes clearer, suitable methods that combine transactive control and empowered consumers are expected to be synthesized and analyzed.

4. Resilient Control

Critical infrastructures are often exposed to extreme and high-impact events such as natural disasters. The vision of Smart Infrastructures, as mentioned earlier, is realized mainly through the incorporation and integration of cyber components of communication and computation into the physical infrastructure (see Fig. 12). These cyber components introduce possibilities of additional high-impact events in the form of directed cyber-attacks which can introduce large latencies in the communication layer as well as outages of service in the physical layer [46]. With this in mind, we argue that the frequency of occurrence of the allegedly low-probability but high-impact events will raise significantly in the future [47] due to the combined presence of cyber attacks and nature-induced emergencies. This is realized by many researchers in various domains [48, 49, 50, 46] who propose that resilience should be a key property which all cyber-physical systems should possess.

Figure 12: Resilience of infrastructures to outages and latencies in a communication network.

Of late, the term resilience and its use is increasingly being discussed (see Fig. 13) in the context of various types of systems ranging from transportation [50],

ecological [51, 52], biological [48], power [46, 47] and more recently of control systems [53, 54, 47]. While an accepted definition of resilience, in the context of systems and control, is yet to emerge, there's acceptance, in general, that the term resilience connotes the ability of a system to withstand and recover from high-impact and severe disturbances.

Figure 13: Usage of word "resilience" over the years according to Google Ngram Viewer

Given the scope of the term, the intersection of resilience with other system-related notions such as robustness, reliability and stability needs to be carefully examined. It's not surprising, in fact, that resilience and robustness are even used interchangeably [49]. Our thesis is that while these two notions are closely related, they characterize different properties of a system and therefore a distinction should be made between the two, as in [47, 55, 56]. In control theory, robustness is a precisely defined notion and refers to a property that characterizes the ability of a system to maintain its normal operation after being subjected to a range of bounded, and small disturbances or uncertainties [57]. It is important to note two aspects of robustness. First, the level of severity and the magnitude of the disturbances with respect to which robustness should be guaranteed are small and not necessarily at a level that can cause the entire system to fail. Second, the performance objective that a robust system should achieve is strict and does not necessarily accommodate any degradation in its performance. In other words, a robust system is expected to function properly and perform close to normal operating conditions in face of these small

perturbations. Resilience, on the other hand, is considered in the context of extreme, rare and high-impact disturbances that drive the system to operate in the proximity of its physical operational limits [56]. As a result, the performance objective of a resilient system is, in general, and should be, more relaxed than that of a robust system and allow for a certain amount of performance degradation. At the same time, it should capture the aspect of criticality of meeting certain critical system objectives over others after the system has been subjected to a high-impact disturbance. Such properties are not necessarily the focus of robust systems.

4.1. Robustness and Resilience in the Context of Smart Grids

In this section, we focus specifically on smart grids and elaborate on the distinction between robustness and resilience. Consider the five well-established operating states of a power system [58, 56] depicted in the figure below. Power

Figure 14: The five possible operating states of a power system

grids can transit from one state to another when subjected to disturbances. Specifically, they can move into an alert state when they experience disturbances that shrink their stability margins, but not affect their regular operational status. Thus, power systems can be characterized as robust when they are able to operate normally (i.e. serving the total electricity demand) under disturbances that only cause transitions between *normal* and *alert* states [56]. In contrast, more severe disturbances can cause power systems to move into an emergency

state where their performance begins to degrade while they experience overloads. Depending on the actions taken at this stage, power grids can potentially move to an *extremis* state where their performance can be significantly degraded while, at the same time, they can experience even greater overloads. Therefore, power grids can be characterized as being resilient when they can return to an alert or normal state from an *emergency* or an *extremis* state, within acceptable time. The minimum, but critical, requirement for a resilient power system returning back from an emergency or in *extremis* state is to supply its critical loads [59]. This is depicted in Fig. 15 below. Any metric that aims to quantify

Figure 15: The load P_D supplied by a power grid following a large disturbance

resilience in power systems has to, therefore, reflect the level and time frame at which such a critical requirement is met after a high-impact disturbance.

The discussion above has been primarily carried out in the context of Smart Grids. The notion of resilience is equally applicable to problems of transportation in Smart Cities [50] as well.

4.2. Evaluating Resilience of Dynamic Real-Time Market Mechanisms in Cyber-physical Power Systems

In this section, we provide a specific illustration of resilience in a power grid problem. A metric for evaluating the resilience of dynamic market mechanisms that captures the aspects discussed above has been recently proposed in [60]. In particular, the proposed resilience metric is denoted by $R(t)$ and is a normalized measurement of the mismatch between dispatched and actual power $R_p(t) \in \mathbb{R}$ at a particular time window, noted as residual power. Specifically, $R(t)$ is defined as:

$$R(t) = 1 - \frac{|R_p(t)|}{R_p^{max}}, \quad R(t) \in \mathbb{R} \quad (13)$$

where $R_p^{max} = \bar{P}_i$ with $\bar{P}_i$ being the maximum power output of the generator that is removed from the grid (considered as a physical outage). We note that the total dispatched power is always approximately equal to the total demand, therefore, we can alternatively normalize the mismatched power with respect to the total demand P_D^{total} , i.e let $R_p^{max} = P_D^{total}$. Such a normalized $R(t)$ can be used to quantify resilience of power systems. This is the approach proposed in [60] where the resilience of an integrated Dynamic Market Mechanism (DMM) is evaluated using a modified IEEE 118-bus test system when subjected to communication failures. In particular, the highest-output generator is assumed to fail in the beginning of each of the following three scenarios. In the first scenario, each of the 84 generator and demand response units is assumed to lose communication with the ISO one at a time, and the corresponding normalized $R(t)$ under the worst link outage is recorded and benchmarked against the outage-free $R(t)$ response (Fig. 16) [60]. In the second scenario, small constant latencies and, in the third scenario, non-uniform latencies were considered in the communication between the market participants and the ISO. Figures 17 and 18, respectively, depict the resulting $R(t)$ response under these two scenarios. The above numerical simulations illustrated that the particular DMM is resilient with respect to single communication link failures (Fig. 16) and small constant

Figure 16: The system responds to a worst-case single-generator failure. The market minimizes residual power in two identical experiments, but one has a communication link outage to a single client - the one that causes the most impact.

Figure 17: The mean latency for each client is increased. The higher latency values reduce the rate of communication, and the convergence speed of the system for different latencies is shown.

latencies (Fig. 17) while, on the other hand, it is not resilient to non-uniform latencies (Fig. 18).

The results above as well as those reported in [61] show that steps can be taken to assess and mitigate anomalous behavior that may occur in the presence of some of these attacks. Much more effort needs to be expended in this direction, which concerns cyber-physical security of smart infrastructures, which is very much at an early stage of research.

Figure 18: The variance in latency is increased for a small mean value. After the system apparently stabilizes, the response begins to oscillate.

4.3. System-theoretic Framework for Resilient Control Design

We conclude this section with a formal definition of resilience that reflects the above discussions and a statement of the resilient control problem.

Definition 1. *Resilience of a system with respect to a class of extreme and high impact disturbances, is the property that characterizes its ability to withstand and recover from this particular class of disturbances by being allowed to temporarily transit to a state where its performance is significantly degraded and returning within acceptable time to a state where certain minimal but critical performance criteria are met.*

We now apply this definition to the following hybrid system, whose model is inspired by that proposed in [47], and is given by

$$\dot{x}(t) = f(t, x, u, w, \theta(t, \alpha, d, l)), \quad x(t_0) = x_0 \quad (14)$$

where $x(t) \in \mathbb{R}^n$, $u(t) \in \mathbb{R}^r$, $w \in \mathbb{R}^p$ are the state, the control input and the deterministic disturbance vector respectively. The discrete state is denoted by $\theta \in \vartheta$ and is parameterized by α , that can take any value among a collection of cyber attacks $\mathcal{A}$, $d \in \mathcal{D}$ that models the possible physical failures, the system operator's action $l \in \mathcal{L}$, and time t . The complexity of the infrastructure and its vulnerability to cyber and physical attack characterizes the function θ .

In particular, ϑ should be defined such that θ taking the values 1 through 5 corresponds to the system in Eq. 14 being in the five modes, *normal*, *alert*, *emergency*, *in extremis* and *restorative* shown in Fig. 14, respectively. With the above system model, we can state the problem statement for resilient control and robust control as follows: The resilient controller's objective is to bring the system back to normal operating mode from any other mode, while the robust controller's objective is to achieve optimal performance in each mode in the face of a disturbance w . The challenge is to carry out a simultaneous design of both robust controllers u and resilient control strategies l that will guarantee robustness against w and resilience against α and d .

5. Concluding Remarks

Control systems have focused on the management of external inputs that direct the performance of a physical system. Examples of successful illustrations of control are ubiquitous, and range from aerospace and automotive systems to process control and robotics. As we move deeper into the 21st century, new frontiers of control are emerging, which pertain to the analysis and synthesis of critical smart infrastructures. Whether in energy or transportation or healthcare, these infrastructures are becoming smart - they monitor themselves, communicate, and most importantly self-govern. Various drivers have enabled this transition, including sustainability concerns, scarcity in resources, economic considerations, and rapid growth in enabling technologies of sensor networks, and computational and communication systems. New topics in systems and control need to be examined in order to design smart infrastructures, and in particular to address their goals of delivering a critical service and to do so with limited resources.

The focus of this paper is on three emerging topics, which include empowered consumers, transactive control, and resilient control. Empowered consumers directly contribute to an active and informed use of any resources available, transactive control serves as a control input to these consumers, through suit-

able incentives including economic ones, and resilience is an integral property to an infrastructure whose primary purpose is to deliver a service reliably to its end user. Each of these three topics presents a host of opportunities for systems and control concepts to be employed and explored. In this paper, an overview of these topics as well as the opportunities were discussed. Two specific illustrations of transactive control with empowered consumers were provided, in the context of smart grids, where concepts related to multi-agents and multi-timescales were shown to be highly relevant. A definition of resilience was presented including an illustration of how it can be assessed and quantified in a smart grid problem.

The problems outlined above clearly illustrate that several opportunities exist for the controls community to lay out the foundation for smart infrastructures. Challenges are present at all levels, from modeling, identification, uncertainty management, adaptation, optimization, and control. Solutions may need to be robust, decentralized, distributed, hierarchical, hybrid, optimal, and resilient. They need to be scalable, easily implementable, and evolve as the infrastructure needs change. At all of these levels, a systems and control approach that provides a blueprint for smart analysis and synthesis lies at the core. We invite all control researchers to participate in this fascinating endeavor.

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