

Foundations of Infrastructure CPS

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Abstract—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 – they monitor themselves, communicate, and most importantly self-govern, which we denote as Infrastructure CPS. Cyber-physical systems are now becoming increasingly prevalent and possibly even mainstream. With the basics of CPS in place, such as stability, robustness, and reliability properties at a systems level, and hybrid, switched, and event-triggered properties at a network level, we believe that the time is right to go to the next step, Infrastructure CPS, which forms the focus of the proposed tutorial. We discuss three different foundations, (i) Human Empowerment, (ii) Transactive Control, and (iii) Resilience. This will be followed by two examples, one on the nexus between power and communication infrastructure, and the other between natural gas and electricity, both of which have been investigated extensively of late, and are emerging to be apt illustrations of Infrastructure CPS.

Index Terms—Infrastructure, Resilience, Demand Response, Transactive Control

I. INTRODUCTION

Definition: *infra•struc•ture* (*noun*) *the basic physical and organizational structures and facilities (e.g., buildings, roads, and power supplies) needed for the operation of a society or enterprise.*

Cyber-physical systems (CPS) are physical systems whose operations are monitored, coordinated, self-governed and integrated by a system of sophisticated computing and communication algorithms. Over the past five years, major advances have taken place in the area of cyber-physical systems, from nano-scales to large scales at the system of systems levels. Examples of CPS range from medical devices and nanorobotics to next generation air transportation, intelligent highway systems, smart buildings, smart grids, and smart cities.

Advances in CPS have been reported at multiple fronts. Fundamental building blocks that combine the discrete, logic based, principles of computation and uncertainties and continuous dynamics of physical systems have been developed. Principles of codesign of control and implementation platform that ensures high control performance with minimal computational and communication resources have been developed. Several tools are being developed for ensuring both cybersecurity and physical reliability in the face of natural and cyber attacks. Tools for evaluating privacy concerns are being synthesized. Benefits are being continuously reported in several application

domains that range from energy and healthcare to aviation, ground transportation, and robotics.

Cyber-physical systems are now becoming increasingly prevalent and possibly even mainstream. It can be argued that at systems level, we have obtained a good understanding of basic properties of stability, robustness, and reliability as well as a good grasp of fundamental properties of hybrid and switched and event-triggered systems that serve as central building blocks for the analysis and synthesis of CPS.

With the above understanding of the basics of CPS at a systems level, we believe that the time is right to go to the next step, Infrastructure CPS, and forms the focus of the proposed tutorial.

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 – monitor themselves, communicate, and most importantly self-govern, which we denote as Infrastructure CPS.

The first of these concerns the end user. In contrast to the role of the consumer in an infrastructure, which is typically a passive one, in a smart infrastructure is more central, and notably an *active* one. Given that the underlying 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, the underlying tools, methodologies, and challenges are all problems that fall within the broad rubric of systems and control.

If one can view the first pillar of empowered consumers as an actuator, the second pillar of a smart infrastructure, Transactive Control, 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 contracts negotiated between the components of the system, in conjunction with or in lieu of traditional controls* [1], transactive control is being explored in depth in the context of a smart grid infrastructure. Some of the basic features and tools that have been examined under this heading are discussed in this paper.

The third pillar is resilience of the infrastructure. Resilience refers the capacity of an infrastructure to tolerate disturbances – both random failures and targeted adversarial attacks – and still continues to operate. In the presence of empowered

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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 infrastructure CPS make the design and analysis of resilience 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 one system may not align with the global requirements leading to compromises. This paper will present some of the tools and methods used to examine the resilience within this context.

This tutorial will focus on three main pillars of Infrastructure CPS: (i) End-user Empowerment, (ii) Transactive Control, and (iii) Resilience. This will be followed by two examples, one on the nexus between power and communication infrastructure, and the other between natural gas and electricity, both of which have been investigated extensively of late, and are emerging to be apt illustrations of Infrastructure CPS. Two examples will be presented that illustrate the main features of smart infrastructures. The first is the nexus between Natural Gas and electricity networks. One of the fastest growing consumers of NG is the electricity sector, through the use of NG-fired power plants. Already a large portion of the electricity portfolio mix in many regions in the US, NG-fired power generation is increasing even further with growing penetration of renewable energy due to the formers fast, on-demand response capabilities, and latters characteristics of intermittency and uncertainty. As a result, NG and electricity networks are getting increasingly linked and interdependent. Recent results from modeling of this interconnection and interdependency will be presented in this paper. The second example deals with the integration of power transmission systems with communication networks for efficient monitoring and control through a *co-design* approach. We will describe a potential way of constructing a distributed multi-loop networked system for wide-area control of large power grids that consists of - (1) a set of distributed optimal control algorithms for damping small-signal oscillations in power and voltages, that will be implemented on the top of (2) a distributed computing infrastructure connected by high-speed wide-area networks, consisting of both Software Defined Networking (SDN)-enabled Internet, and the traditional layer-2 or layer 3 Internet.

II. FOUNDATION 1: 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 fundamental assumption has been that demand always remains inelastic. 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 being increasingly investigated in the context of Smart Grid.

Demand response denotes the concept of adjustable demand in response to grid conditions and incentives and has a history dating back at least to the late Fred Schweppe's pioneering work on homeostatic grid control in the 1970s [2]. By allowing consumption to be generated alongside of generation, the premise is that one can manage uncertain and variable renewable generation in a much more efficient manner (see Figure 1) 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.

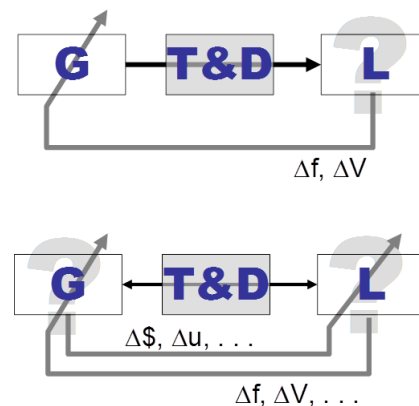


Fig. 1. The role of an empowered consumer is to adjust their consumption in response to an incentive that may be financial, sustainability based, or through a social network [3].

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 [4]. 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.

While this is a highly active area of research, with various approaches being employed by research groups around the world, we briefly mention three topics that are being investigated in detail:

- 1) *Dynamic modeling 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 Figure 2, 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 devices. Such models have begun to be employed both in the context of smart grids [5] and smart cities [6].

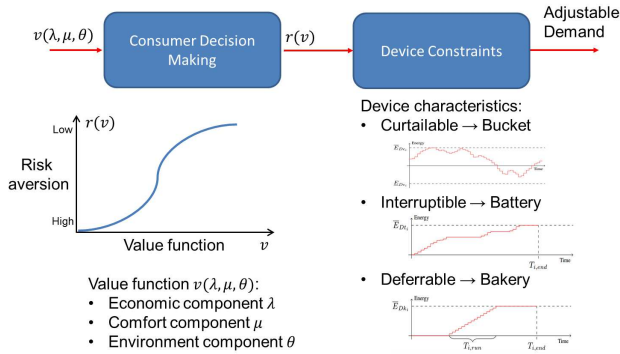


Fig. 2. The components of an empowered consumer model in the context of smart grids.

2) Global optimization using local and distributed control:

This is a broad topic that is being addressed by a number of researchers in the control community, both from a theoretical perspective (see for example, [7], [8]) and from an application perspective, (see for example, [9], [10]). The challenge here is to ensure local performance metrics such as stability robustness at faster time scales, and optimization at slower time scales. Any control solutions that are proposed must accommodate realistic constraints that are imposed by the end user dynamics and decision making, as well as the constraints imposed by on the associated communication infrastructure.

3) Risk-limiting approaches:

The main idea behind the empowered users is that they are endowed with a flexibility in availing themselves of resources that an infrastructure provides. By providing suitable incentives to the consumers, the goal is to ensure an optimal utilization of these resources. For example, as there is more surplus of inexpensive energy due to growth in renewables, electricity prices decrease, and if consumers are flexible in their consumption with less consumption when prices are high and more when prices are low, then this flexibility can be utilized to accommodate variability from renewables. However, all end users, whether individual consumers, or larger organizational entities, are risk averse. Models as outlined in Figure 2 are often inadequate when it comes to decision making that also manages risks that may be incurred over a larger time-scale. Recent results such as [11], [12] attempt to address this problem using a multi-stage stochastic formulation by making decisions of dynamic contracts

for consumption valid for a block of time, with the blocks and decisions updated as operations approach real-time.

III. FOUNDATION 2: TRANSACTIVE CONTROL

A concept that is eliciting significant attention of late is Transactive Control [1], [13], [15], a feedback control strategy enabled through economic contracts. 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.

As is clear from the above description, the underlying problem is one of a socio-economic-technical system and as such, the underlying tools for its analysis and design are to be assembled not only from systems and control, but also from 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, as their implementation will have to be approved by entities related to policy and regulation.

In what follows, a snapshot of market-based approaches that have been adopted in the area of Smart Grid will be presented, summarized concisely in [14].

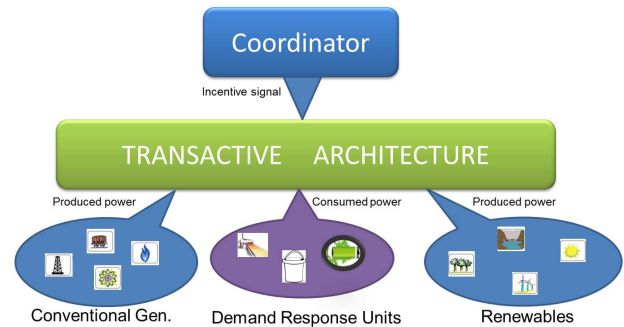


Fig. 3. Transactive architecture engages various end users in a decision making process whose objective is to maximize economic benefits for all involved entities.

Market-based approaches for achieving socio-economic-technical system objectives evolve around two groups of market players. In the first group are the load aggregators whose primary responsibility is to represent individual users at the wholesale electricity market. While representing end users, it is at times in their interest to induce desired demand behavior of the aggregated groups of loads, which is an effort realized by using incentive signals through transactive control architecture. To accomplish this, load aggregators can design retail market rules using mechanism design and contract theory, while observing given wholesale market structure and public utility commission issued regulations regarding retail electricity markets.

In the second group are the individual users, who are buying electricity from the load aggregators via retail contracts. Understanding of electricity usage and load capabilities empowers

the end users to make the adequate decisions under given retail market structure and respond to the incentives in the most efficient manner.

To design an adequate transactive architecture it is necessary to represent behavior of end users and the load aggregators in a truthful way. Looking at the problem from the perspective of a load aggregator, an end user i could be described with one or more of the following attributes: i) the physical constraints of its loads in terms of consumed power $P_i \in \mathcal{P}_i$, ii) the consumed power valuation function $v_i(P_i, \theta_i)$ where $\theta_i \in \mathcal{T}$ is a random variable representing a particular realization of a consumer type, iii) and by the consumer's utility function $u_i(P_i, \lambda_i, \theta_i)$ where $\lambda_i \in \mathbb{R}$ denotes the price of electricity for consumer i .

The coordinator is usually in charged of maximizing social welfare of the market participants, i.e. it is solving the following optimization problem

$$\begin{aligned} \max_{P_1, \dots, P_n} \quad & \sum_i v_i(P_i, \theta_i) - c \left(\sum_i P_i \right) \\ \text{st:} \quad & P_i \in \mathcal{P}_i \\ & g(P_1, \dots, P_n) \leq 0 \end{aligned} \quad (1)$$

where $c(\sum_i P_i)$ is the cost of purchasing and supplying the entire load under the load aggregator and $g(P_1, \dots, P_n) \leq 0$ are the transportation constraints. Problem (1) can be easily restated as a dynamic programming problem if the load aggregator needs a solution over a certain time horizon.

Fundamental nature of the problem (1) depends on the information available to the load aggregator who could have either complete or incomplete information, and on the rationality assumption for the user who could behave either strategically or non-strategically.

If complete information is available to the load aggregator and the end users are non-strategic then the problem (1) is regarded as the centralized optimization or optimal control problem. In this scenario, load aggregator determines the consumed power P_i for all users. Such approach is suitable, for example, university campus operation.

If the load aggregator possesses the complete information about the user constraints and their valuation function but cannot directly control the consumed power since the users are strategic, then the problem (1) is regarded as a Stackelberg game that can be solved using bi-level optimization. In this approach, the load aggregator first determines the price λ_i and the user optimizes its own utility accordingly. Some references in this area include [16], [17], [18], [19].

If the end users are non-strategic but the load aggregator does not possess the complete information, then the problem (1) becomes a decentralized optimization problem. The solution methods in this area often use iterative information exchange [20], [21], [22].

Finally, mechanism design is used if load aggregator does not have complete information and the end users are behaving strategically. The goal of mechanism design is to determine such market rules under which the game theoretic equilibrium matches the one of the social welfare. Discriminatory

pricing [23], [24], [25] and uniform-pricing mechanisms are typical representatives of mechanism design.

With these various market based approaches, while many of the building blocks for transactive control are in place, several challenges remain, especially in the realm of scalability, reliability and risk-sharing. Notably, scalability has to be obtained while observing the physical limitations of the communication and computation hardware, and time-constants of physical processes underlying the infrastructure. This requires tighter integration of the described market approaches with the technical capabilities of the infrastructure. Second, integrity of infrastructure operation often requires guarantees from the controller in terms of technical performance. Since market-based approaches are a type of indirect control, often even having human in the loop, guarantees on technical performance are harder to obtain. Third, risk-sharing between participating entities is crucial for bringing transactive control to practice, and thus, the tractability of the implemented control method plays a crucial role. Further developments in scalability, reliability and risk-sharing are required to successfully transition existing market approaches to practice.

IV. FOUNDATION 3: RESILIENCE

The survivability of critical infrastructures in the presence of security attacks and random faults is of national importance. These infrastructures are spatially distributed across large physical areas and consist of heterogeneous cyber-physical components interconnected with complex peering and hierarchical networks. Networked Control Systems (NCS) and Supervisory Control and Data Acquisition (SCADA) systems are widely used to monitor, control, and remotely manage infrastructures over private or shared communication networks. The cyber-physical systems (CPS) permit synergistic interactions between physical dynamics and computational processes. Wide deployment of Information and Communication Technologies (ICT) results in higher reliability and lower operational costs relative to the traditional proprietary and closed systems. However, as several recent incidents indicate, the CPS today are facing new security threats driven by their exposure to ICT insecurities and these are bound to increase with the scale and complexity of infrastructure CPS.

Resilience in an infrastructure refers to the ability to provide and maintain an acceptable level of service in the face of various faults and attacks that challenge normal operation. For example, a denial of service attack may have some impact on a system and hence some immediate impact on the services it offers to the end users. The system will then adapt and recover and the service levels improve and at some later time full service may be restored even when the attack has not completely subsided.

A distributed cyber physical infrastructure has a layered architecture consisting of regulatory control (layer 1), supervisory control (layer 2), and a management level (layer 3). This architecture enables robust composition of multilevel controllers, and permits operators to use strategies to limit the effects of faults and attacks. The regulatory control layer directly interacts with the underlying physical infrastructure

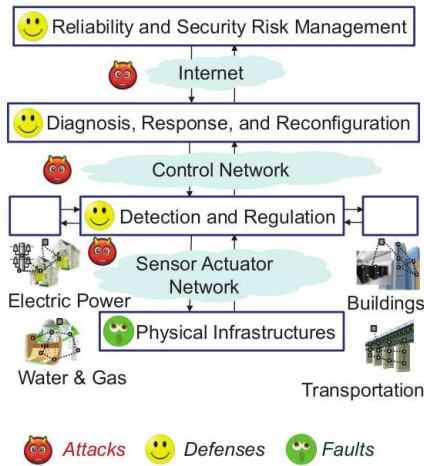


Fig. 4. A Layered architecture for management of distributed infrastructure [26].

dynamics through a network of sensors and actuators. These physical field devices are connected to programmable logic controllers (PLCs) or remote terminal units (RTUs), and implement detection and regulation mechanisms that are primarily reactive in nature and use local information. The regulatory controllers (or PLCs) interact with the supervisory controllers via a control network.

At the supervisory control layer, model-based diagnostic tools are combined with optimal control-based tools to ensure on-time response to distributed failures and threats. The supervisory workstations are used for data logging, diagnostic functions such as fault diagnosis, and supervisory control computations such as set-point control and controller reconfigurations. The physical infrastructure control inputs u are processed to produce several measurements y that represent the response of the physical infrastructure. The control design task in the presence of attacks, is to choose the input u so that the output response $y(t)$ satisfies the performance and stability requirements. Because the physical process is large and complex, it may consist of several energy cells with load and generation entities distributed over a large geographical area, the appropriate choice of u is in not straightforward

Resilience in infrastructure CPS is an area of active research, with various approaches being employed by research groups to model and analyze how their control algorithms and systems fair in the presence of attacks and failures. This tutorial will focus on the following areas:

1) Threat modeling

The three fundamental properties of information, namely, confidentiality, integrity, and availability can be attacked in infrastructure CPS. Confidentiality refer to the concealment of data, ensuring it remains known only to the authorized parties. *Disclosure attacks* enable the adversary to gather sequences of data \mathcal{I}_k from the calculated control actions u_k and the real measurements y_k . The physical dynamics of the system are not affected by this type of attack. Integrity relates to the trustworthiness of data, meaning there is no unauthorized change to the information between the source and destination.

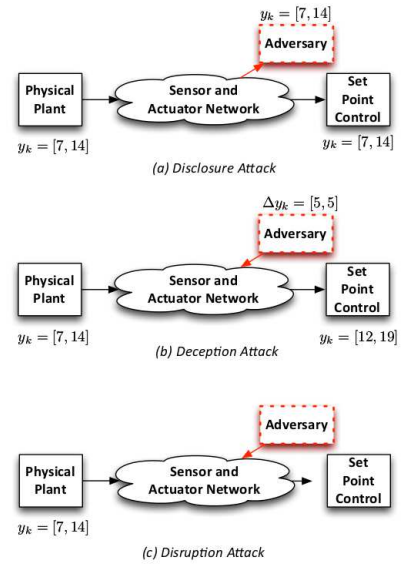


Fig. 5. Cyberattacks on the communication network: (a) data confidentiality violation by a disclose attack, (b) data integrity violation by false data injection attack, (c) data availability violation by a denial of service attack.

Deception attacks modify the control actions u_k and sensor measurements y_k from their calculated or real values to the corrupted signals \tilde{u}_k and \tilde{y}_k , respectively. The deception attacks are modeled as

$$\begin{aligned}\tilde{u}_k &\triangleq u_k + \Delta u_k \\ \tilde{y}_k &\triangleq y_k + \Delta y_k\end{aligned}$$

where the vectors Δu_k and Δy_k represent the manipulation to the respective data channels. Availability considers the timely access to information or system functionalities. *Disruption attacks* prevent the transmitted data from reaching the desired destination. Such attacks can impact the system by blocking the data or feedback signals, using denial of service attacks, replay attacks, or zero dynamics attacks [27].

Figure 5 illustrates the three categories of attacks and how they violate the security properties. In all three cases, the physical plant is sending a measurement vector $y_k = [7, 14]^T$ to the controller through the communication network. This was intended to be a private message to be known only to the plant and the controller. In this tutorial we will discuss how to model and experiment with all three types of attacks [26].

2) Experimentation frameworks

As demand response models [28] grow in participation, Internet-like dynamics will influence algorithm operation. Models of dynamic markets that do not consider such network issues may prove unreliable or inconsistent when implemented in realistic communication environments. The influence of the dynamics of communication networks on markets and their convergence, when driven by faults and failures, should to be analyzed in detail before they can adopted widely on the smart grid.

In this tutorial, we present a framework to evaluate the resilience of dynamic market and control mechanisms

in the presence of network dynamics by separating its communication components, the independent system operator (ISO), generators, and loads, across the network on the DETER testbed. We will present a set of resilience scenarios and execute them to evaluate the performance of markets and controls under the stress of faults and failures [29].

3) **Distributed optimization with attacks**

The current state-of-the-art centralized communication and information processing architecture of WAMS will no longer be sustainable under the various threats discussed above. Modeling and evaluating the infrastructure in the presence of attacks is essential [30]. Motivated by this challenge, in this tutorial we will present recent results of implementing wide-area monitoring algorithms over a distributed communication infrastructure using massive volumes of real-time PMU data. Our goal will be to provide an example of how distributing a monitoring functionality over multiple estimators can guarantee significantly more resiliency against large scale cyber attacks [31]

V. EXAMPLE 1: NEXUS BETWEEN ELECTRICITY AND NATURAL GAS INFRASTRUCTURES

One of the most prominent sectors of the 21st century that has far reaching effects on all citizens of this world is energy. Two of the most critical infrastructures that serve as a substrate of the energy sector are electricity and natural gas (NG). The Shale Gas Revolution has changed both the availability and prices for natural gas (NG) in the past decade. Combined with an aging coal fleet, and the need for increasingly flexible power generation plants to facilitate the addition of renewable power generation, the reliance of the electricity sector on NG has risen dramatically. As storage of large quantities of the fuel is limited to specific geological formations or costly, NG-fired generation plants use gas as it is delivered to them. This leads to one just-in-time resource (natural gas) being used by another just-in-time resource (electricity). The dependence between these two sectors has led to concerns over scheduling, transportation, and communication.

The electricity infrastructure consists of generators from which power is transferred via long distance, high-voltage transmission lines, with the voltage gradually stepped down through distribution systems to the end-user. With demand largely treated as an uncontrolled, exogenous input, electric utilities have an assumed "obligation to serve" in which generation needs to be operated to meet this exogenous load demand at all times [32]. This balance between supply and demand is typically carried out by independent system operators. The NG infrastructure is quite similar to the electricity infrastructure, in terms of the network topology - it consists of transmission (pipelines), producers (wells), storage, and consumers. Pipelines use compressors along the line to create the flow of NG from the injection point on the line to the consumer of the NG. NG marketers, facilitate movement of NG by coordinating the sale of gas quantity and pipeline capacity contracts.

There are significant operational, contracting, planning, and regulatory differences between the two infrastructures as well [33]. The underlying physics, that of the path of an electron from generation to the consumer versus the path of fuel from production wells to the end user, are different, with the former moving at the speed of light, and the latter significantly below the speed of sound. Storage is highly expensive, and therefore scant in the former, while simple and necessary in NG. Economies of scale are much larger in electric power transmission projects, as opposed to NG transmission. Retrofitting a line to increase transmission capacity is prohibitively expensive. It is more economical to install the required capacity of a transmission line initially than to retrofit the line later. Increased capacity can be obtained with relative ease in the latter case by raising the pressure at NG pipelines. Control of individual constituents is near to impossible in the electric sector (ex. power flows in transmission segments), in relation to the NG sector (ex. NG flows in pipelines).

That the electricity and NG infrastructures are highly interdependent is easy to see. The most common instance in places such as Northeastern US, is during cold snaps, when the demand for electricity and NG increase simultaneously for heating requirements. NG price hikes due to pipeline constraints increase marginal costs of NG-fired generation, which in turn leads to dramatic increases in market prices for electricity. This interdependence is increased further with more emphasis on NG-fired generation in general as coal plants retire due to environmental regulations. And most importantly, with increasing emphasis on renewables, the inevitable features of intermittency and uncertainty in renewables is necessitating increased dependence on NG-fired generators which are capable of fast, on-demand response for power balance. Coordination between the two infrastructures is therefore essential for reliable power generation. Any interruption or pressure loss in critical NG pipeline systems may lead to a loss of multiple NG-fired generators, thereby reducing the supplied power and therefore jeopardizing the power system security.

Yet another example of the need for coordination occurs in the context of markets. In deregulated electricity markets, the supply of electricity is organized through a day-ahead and real-time market, which requires accurate information on generator availability and prices as well as consumer demand. With increased reliance on NG, information on fuel availability to NG-fired generators is of increasing concern. This is complicated by the structure of the NG sector, which has separate markets for buying NG quantities and buying NG transportation, and lacks flexible market mechanisms for a proper allocation of both products of gas quantity and capacity available for transportation. Pipeline capacity contracts can be classified as firm or interruptible. Firm contracts are long term and are paid on a monthly basis and are typically used by Local Distribution Companies (LDC). Moreover, these contracts incur an additional reservation charge which pays off investment in pipeline infrastructure. Interruptible contracts are flexible and typically used by gas-fired generators [34]. Independent System Operators in the electricity infrastructure need to know the availability of their generation plants in order to dispatch them in a manner that both assures system

reliability and minimizes the total system cost. It is difficult for these system operators to rely on NG-fired generators which could potentially have their fuel curtailed.

In what follows, we provide two examples of the nexus between electricity and NG infrastructures, and how a CPS approach can potentially help improve their coordination. Details of these results may be found in [35] and [36].

A. Case Study 1:

With the growing interdependency of NG and electricity, the inefficiencies caused by the misalignment of the markets has also grown. For example, the commodity market is most liquid between 8 am and 9 am [37]. If the timing of the markets is such that NG-fired generators need to buy fuel outside of these times, which is currently the case, it can be difficult and costly because there are fewer market participants. The greater the market misalignment, the greater the uncertainty NG-fired generators face in NG quantity and price. In some energy markets, NG-fired generators do not receive their dispatch schedule from the power system operators until after the pipeline capacity market has already closed. Also, NG-fired generators need to coordinate their dispatch and fuel delivery over two NG days (specifically, the NG intra-day market of the previous day, and the NG intra-day market of the current day) in order to meet their day ahead electricity obligations due to the timing of the markets and NG flow start times.

When NG-fired generators fail to nominate transportation for the right amount of NG to meet their final schedule from the ISO, they often over or undertake NG from the pipeline [38]. Overtaking is taking more than the scheduled quantity and undertaking is leaving NG in the system that was previously scheduled to be removed. Pipeline operators will resell this excess NG and charge the consumer extra based on how much they over or undertake [39]. Since pipelines generally schedule transmission assuming the NG is taken throughout the day in regular increments, when generators overtake NG unexpectedly, this creates balancing problems for the pipeline system operators [37]. When there are difficulties in maintaining appropriate pressure in the system, operators may limit the amount of NG allowed to be overtaken and undertaken and also implemented rateable takes [38]. If generators know they will be restricted to 1/24th of their total nomination each hour with a rateable take, the generators may over-nominate NG so that they have more than they need, and sell the NG that they do not consume in during hours where they are not needed for electricity production. In addition to the potential loss of value on the re-sold fuel, NG-fired generators would also be faced with costly imbalance fees, making overtaking, undertaking, and rateable take scenarios quite expensive [39].

We consider a simple 4-bus network, which consists of three generators; two dispatchable (base unit and peaking unit) and one non-dispatchable, and two consumers who demand power from the system (see Figure 6). The conventional dispatchable generators have no fuel uncertainty and are denoted G1 and G2 and the non-dispatchable generation unit is denoted as G3 and is a NG-fired generator with fuel uncertainty.

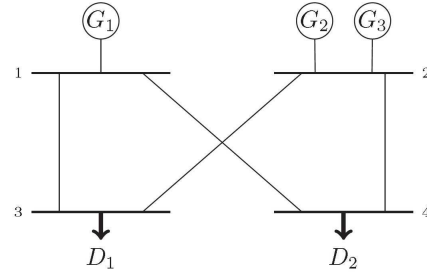


Fig. 6. IEEE-4bus network with G1 and G2 being conventional generators and G3 being a NG-fired generator with fuel uncertainty from interruptible contracts and market misalignment.

The problem that we address with this system is the optimization of Social Welfare S_W defined as

$$S_W = \sum_{j \in \mathcal{D}_q} U_{D_j}(P_{D_j}) - \sum_{i \in \mathcal{G}_c} C_{G_{c_i}}(P_{G_{c_i}}) - \sum_{l \in \mathcal{G}_{ng}} C_{G_{ng_l}}^{tot}(P_{G_{ng_l}}) \quad (2)$$

where

$$\begin{aligned} U_{D_{a_j}}(P_{D_{a_j}}) &= b_{D_{a_j}} P_{D_{a_j}} + \frac{c_{D_{a_j}}}{2} P_{D_{a_j}}^2 \\ U_{D_{s_j}}(P_{D_{s_j}}) &= b_{D_{s_j}} P_{D_{s_j}} + \frac{c_{D_{s_j}}}{2} P_{D_{s_j}}^2 \\ C_{G_{c_i}}(P_{G_{c_i}}) &= b_{G_{c_i}} P_{G_{c_i}} + \frac{c_{G_{c_i}}}{2} P_{G_{c_i}}^2 \\ C_{G_{ng_l}}(P_{G_{ng_l}}) &= b_{G_{ng_l}} P_{G_{ng_l}} + \frac{c_{G_{ng_l}}}{2} P_{G_{ng_l}}^2 \end{aligned} \quad (3)$$

subject to the following consumption, generation, and network constraints

$$\begin{aligned} & - \sum_{i \in \theta_n} P_{G_{c_i}} - \sum_{l \in \gamma_n} (P_{ng_l} + \Delta_{ng_l}) + \sum_{j \in \psi_n} P_{D_j} \\ & + \sum_{m \in \Omega_n} B_{nm}(\delta_n - \delta_m) = 0, \quad \forall n \in N \\ & B_{nm}(\delta_n - \delta_m) \leq P_{nm}^{max}, \quad \forall n \in N, \forall m \in \Omega_n \\ & P_{D_{s_j}} = P_{D_{s_j}}^{ref}, \quad j \in \mathcal{D}_q \\ & P_{D_{a_j}}^{ref} \leq P_{D_{a_j}}, \quad j \in \mathcal{D}_q \\ & P_{G_{c_i}} \leq P_{G_{c_i}}^{max}, \quad i \in \mathcal{G}_c \\ & P_{G_{ng_l}} \leq P_{G_{ng_l}}^{max}, \quad l \in \mathcal{G}_{ng} \end{aligned} \quad (4)$$

The coefficients $b_{D_{a_j}}$, $b_{D_{s_j}}$, $c_{D_{a_j}}$ and $c_{D_{s_j}}$ are consumer utility coefficients. The utility of the total consumption $U_{D_j}(P_{D_j}) = U_{D_{a_j}}(P_{D_{a_j}}) + U_{D_{s_j}}(P_{D_{s_j}})$. The incremental and base price coefficients determine the behavior of the adjustable portion of the demand. The consumption values are constrained; $P_{D_{a_j}}$ and $P_{D_{s_j}}$ must evolve so that in equilibrium, $P_{D_{a_j}}$ reaches a value no smaller than the derived value $P_{D_{a_j}}^{ref}$ and $P_{D_{s_j}}$ reaches the desired value $P_{D_{s_j}}^{ref}$. The coefficients for the generators are based on values used in [40], with the base cost prices for the three types of generators modeled changed to reflect current energy prices from the EIA's Electricity Power Annual report [41]. The base cost is calculated by taking into account the penalties pipelines

imposes on generators for taking fuel off of the Algonquin NG pipeline which services the New England area [39]. The values for the consumer utility coefficients are as listed in Table II. In order to limit the amount of adjustable demand so that the effects of NG uncertainty can be studied better, the values in bold for U_{Da_j} have been modified from what was used in [40]. The incremental cost coefficient c_{Da_j} is set at a larger negative value than the shiftable demand so that consumers have lower willingness to adjust consumption and have a higher base utility of using electricity, much like a data center which would not change their consumption of electricity even if prices rise to very high levels. A dynamic market mechanism based approach, developed recently [15], [43], [42] was used to determine the optimal generation and consumption profiles.

The results are summarized in Figures 7 and 8. Increases in fuel uncertainty decreases Social Welfare in a non-linear manner, with a drastic change in slope at higher levels of uncertainty as seen in Figure 4. This also implies that aligning markets and improving coordination can raise Social Welfare. Increasing the level of demand response through the shiftable Demand Response method outlined as in [40] dramatically increases the Social Welfare of the system, particularly for low levels of NG uncertainty (see Figure 5). These results show that small problems with NG uncertainty do not necessarily need to be solved by changing the NG market structure, but can instead be solved through incentivizing measures like Demand Response in electricity markets.

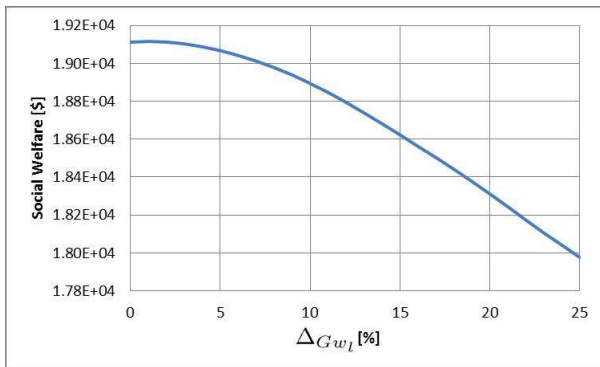


Fig. 7. The Social Welfare at each point Involves looking at a 24 hour period. The results show that as uncertainty in the cost of fuel increases, the effect on Social Welfare grows dramatically.

B. Case Study 2

Case study 2 addresses market discrepancies, communication, and interactions within the NG-E infrastructure. From Case study 1, Δ_{Gw_t} in Figure 4 was the uncertainty in fuel necessary for power supply. Within the interdependent infrastructure, this uncertainty in gas supply results from uncertainty in renewable generation as well as uncertainties within obtaining gas commodity from the marketers of gas in the gas markets. We evaluated the impact of unequal access to gas, given that natural gas fired power plants (NGPPs) are on non-firm contracts with unequal access to the gas markets.

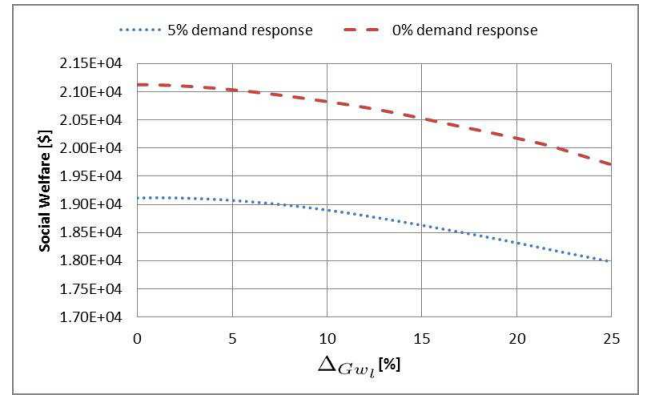


Fig. 8. The addition of just 5 percent shiftable Demand Response dramatically increases Social Welfare, regardless of natural gas uncertainty levels.

There are several information asymmetries that exist within the interdependent gas-electric transactions given that they are all bilateral. The terms of the contract created between the natural gas marketer and the NGPP is private and there is no central ISO to optimize over the contract terms across all market participants. Hence, the transaction between the marketers or sellers of natural gas and the NGPPs owning a portfolio of entirely NGPPs can be modeled as a second degree price discrimination mechanism design problem [44]. The main decision variable is the quantity of gas commodity that is transacted, and this depends upon the type of consumer whether the NGPP is a baseload or a peaker plant preferring a firm or a non-firm contract. The mechanism design model between marketers and NGPP is modeled in the secondary release capacity market and spot commodity market. Five marketers and five NGPPs are the main players in the negotiations (see Figure 9), where 25 contracts are offered by the marketers to each NGPP, for either firm or interruptible service. Each contract is offered by a marketer at a negotiated price, quantity (and eventually type of contract that can be either accepted or not by the consumer).

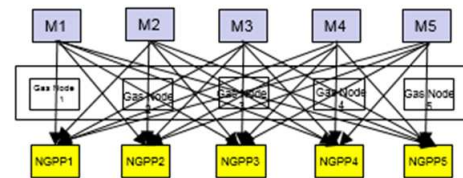


Fig. 9. A simplified structure of the natural gas trading market.

The gas-electric interdependency can be modeled as a two-stage game on the natural gas side. The first stage comprises transactions between the marketers/LDCs and the pipeline operators, where the marketers/LDCs can purchase capacity on primary firm or interruptible contracts. They generally are price-takers from pipeline operators on primary markets. In addition, the marketers will consider consumer demand when obtaining/negotiating capacity on the secondary release market. The first stage game on the electricity side is the bid offer between the NGPP and the ISO. The contract negotiated

between marketers and NGPPs for price, quantity, and type of service (firm or interruptible) is the second stage subgame of interest. Every variable in the first-stage natural gas and electricity games is assumed to be a parameter in the second stage subgame.

While the goal is a mechanism design optimizing each of the 10 players' individual profits, thus far the constrained optimization is a gas dispatch problem co-optimizing the profits of each marketer where the constraints are a capacity, nonzero and demand constraints.

Actual data from the state of Massachusetts was used in the initial analysis. Monthly data was obtained from the EIA and disaggregated into daily demand data utilizing a 2-parameter curve fit and regression method. Five main receipt nodes exist in Massachusetts and it was assumed all demand was satisfied via supply from the Algonquin pipeline. Therefore, one marketer and one NGPP was placed on each of the five main receipt points of gas. Assumptions were made as well on the amount of capacity available (pipeline capacity demand by all other non-electric gas consumers).

In the figure x, results from the gas dispatch model utilizing real data show what the dispatch is given a certain percentage of unequal access to the secondary market (implying interruptible contracts) is for each of the 5 NGPPs in scenarios of unequal and equal access. An assumption of equal access to the secondary market implies firm contracts and unequal access was assumed to be 60% of the secondary release capacity market calculations for all days during the time period of interest. Within this time period, the ratio of available pipeline capacity to quantity allocated or dispatched to the NGPP on each day is calculated and shown below. If the ratio is high, it was cut off at the value of 5 to more easily visualize the daily differences. The first plot below in Figure 10 shows that there is more variation within the ratios day to day. That is, fewer days have a high available capacity to quantity dispatched ratio, and more fall between 1 and 5. In addition, comparing the top plot (unequal access to release capacity market) to the bottom plot (equal access to the release capacity market) there are more days in which the ratio is 1 or 0. That is, the capacity available to that NGPP on that day is less than what is necessary to produce and no gas is allocated to that NGPP on that day. NGPPs are getting curtailed more frequently with unequal access to the market.

The top plot within Figure 10 shows that there exists more uncertainty in obtaining gas when NGPPs have unequal access to the market (greater number of days of curtailment). Therefore, the $\Delta_{C_{w_1}}$ uncertainty in obtaining fuel for power can become larger, and social welfare decreases even more, given uncertainties within the natural gas markets due to contract design and incentives as well.

VI. EXAMPLE 2: INTEGRATING POWER SYSTEMS AND COMMUNICATION NETWORKS THROUGH CONTROL CO-DESIGNS

In this section we will present some ideas on how communication and power infrastructures can be integrated with each other for better performance, control, efficiency, and reliability

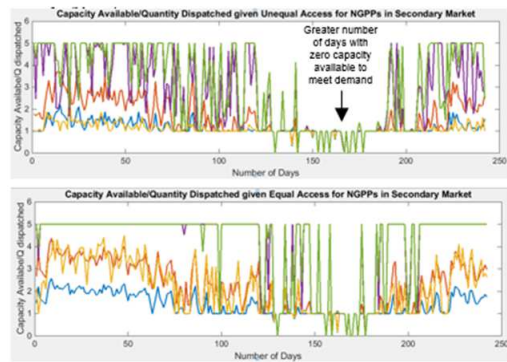


Fig. 10. Comparison of impact that unequal access (top plot) to equal access (bottom plot) within the secondary release capacity market have on curtailment of gas.

of energy networks. Although a general power system consists of three main stages - namely, generation, transmission, and distribution, the greatest challenges in communications lie on the transmission side. The focus of our discussion will, therefore, be on transmission-level controls, especially using wide-area measurement systems (WAMS). The WAMS technology using Phasor Measurement Units (PMUs) has been regarded as the key to guaranteeing stability, reliability, state estimation, control, and protection of next-generation power systems [45]. However, with the exponentially increasing number of PMUs deployed in the North American grid, and the resulting explosion in data volume, the design and deployment of an efficient wide-area communication and computing infrastructure is evolving as one of the greatest challenges to the power system and IT communities. For example, according to UCalug Open Smart Grid (OpenSG), every PMU requires 600 to 1500 kbps bandwidth, 20 ms to 200 ms latency, almost 100% reliability, and a 24-hour backup. With several thousands of networked PMUs being scheduled to be installed in the United States by 2018, WAMCS will require a significant Gigabit per second bandwidth. The challenge is even more aggravated by the gradual transition of the computational architecture of wide-area monitoring and control from centralized to distributed for facilitating the speed of data processing. The existing local-area network (LAN) or Internet based communication, as well as the centralized computing infrastructures will no longer be sustainable under such a data-burst, especially with strict real-time requirements.

One of the biggest roadblocks is that the current power grid IT infrastructure is rigid and low capacity as it is mostly based on a closed-mission specific architecture. The current push to adopt the existing TCP/IP based open Internet and high-performance computing technologies such as the NASP-net [46] would not be enough to meet the requirement of collecting and processing very large volumes of real-time data produced by such thousands of PMUs. Secondly, as pointed out before, the impact of the unreliable and insecure communication and computation infrastructure, especially the long delay and packet loss uncertainty over the wide-area networks, on the development of new WAMS applications is not well understood. For example, as shown in Figure 11, uncontrolled delays in a network can easily destabilize

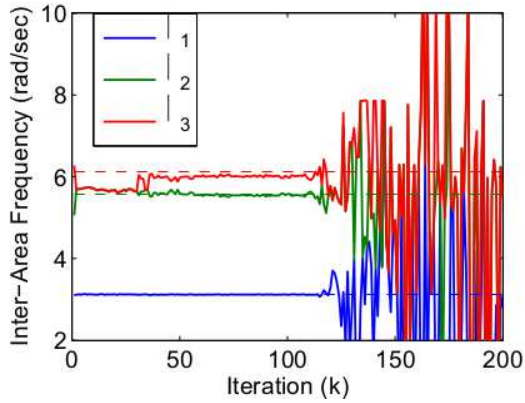


Fig. 11. Divergence of ADMM with delays

distributed estimation algorithms for wide-area oscillation monitoring. This figure is taken from our recent paper [47], where we used a distributed optimization algorithm called Alternating Direction Multiplier Method (ADMM) [48], [49] for estimating frequencies of oscillation from PMU data. Finally, and most importantly, very little studies have been conducted to leverage the emerging IT technologies, such as cloud computing, software defined networking (SDN), and network function virtualization (NFV), to accelerate the development of WAMS. In the following subsections we will discuss how co-design strategies between communication and power systems can be exploited to surpass this roadblock. We show explicitly how multitudes of geographically dispersed PMUs and PDCs can communicate with each other co-operatively for the successful execution of critical transmission system operations, how the various binding and interactive factors in the distributed system can pose bottlenecks, and, finally, how these bottlenecks can be mitigated to guarantee the grid stability and performance. Although discussed primarily for wide-area control, these co-design methods will support any other distributed decision-making process such as wide-area protection, and will also foster newer applications such as distributed power dispatching.

A. Networked Control System and Power Grid

There are extensive studies on the impact of network-induced delay and packet loss on the stability of dynamic physical system or plants connected to a controller via communication networks [50]. The general approach is to derive an upper bound on the network delays, typically modeled as Markov Chains, and design *delay-tolerant* robust controllers using H_∞ , H_2 , linear matrix inequalities (LMI), and other convex optimization methods using semi-definite programming tools [52], [53]. Conventional centralized wide-area controllers have been proposed in [54]-[58], with some recent works on delays [59]-[63]. However, majority of these designs are much more conservative than necessary since they are designed for the worst-case delays. The need for having accurate delay models and network synchronization rules is absolutely critical for wide-area control of power systems since the time-scale of the physical control loop is in the order of tens of seconds to a few

minutes, while the spatial scale can range over thousands of miles, for example the entire west coast of the US. The existing PMU standards, IEEE C37.118 and IEC 61850, only specify the sensory data format and communication requirements. They do not indicate any *dynamic* performance standard of the closed-loop system. That, in fact, is the main motivation for our discussion on co-designs, where we can explicitly show how the closed-loop dynamic responses of phase angles, frequencies, voltages, and current phasors at any part of a grid model are correlated to *real* (not simulated) network delays, that arise from transport, routing, and most importantly, from scheduling as other applications are running in the network.

B. A Co-design Architecture for Wide-Area Control

Figure 12 shows a schematic diagram for a distributed implementation of a network control system for wide-area control of power grids. As we can see, there are three fundamental control loops that interact over different time-scales:

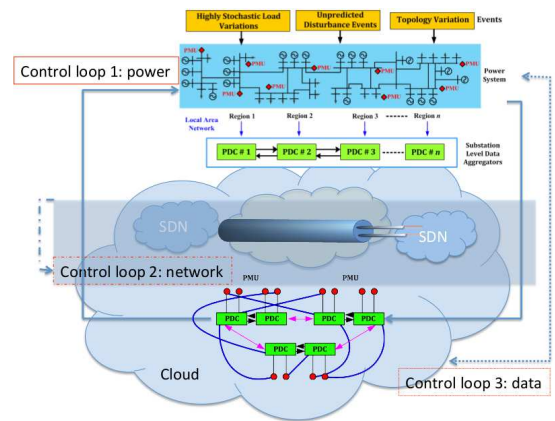


Fig. 12. DistinctGrids system

- Control loop # 1: Distributed state-estimation and control:** This is the control-loop that collects PMU data from different buses in the power system, transmits them to the wide-area communication network (such as GENI), assigns them to various spatially distributed virtual machines (VMs), runs a distributed state estimation and control algorithm between the VMs, and finally transmits the control signal back to the actuators in the power system such as power system stabilizers (PSS) and FACTS devices.
- Control loop # 2: SDN-based real-time communication control:** Given the co-existence of the underlying legacy networks (PLC, IP, Ethernet), and more advanced networks, the application-level overlay SDN network will be created and operated to serve different wide-area applications by actively controlling the stringent real-time and reliability constraints. Furthermore, co-allocation of NFV middle boxes and data processing VMs in the distributed cloud environment will be implemented so that the substation functions can scale out to include virtual middle boxes outside the physical stations. That way the control algorithm running in Loop 1 can be made more efficient as data security and privacy guarantees

can be dynamically added along with data movement and aggregation.

- **Control loop # 3: Cloud based data collection and processing control loop:** Based on the spatial distribution of the PMUs, their data rate and processing requirements on the CPU and memory, distributed virtual PDC clusters will be created and reconfigured in the Cloud, in order to further improve the latency and fault tolerance guarantees of Loop 2.

The details of each of these three loops are described next.

1) *Loop 1: Physical Layer Control:* We consider the power grid to be divided into M coherent areas belonging to M different utility companies [58], where area i has N_i states and P_i controllers. Sorting the states in terms of the areas, we may write its dynamic model as

$$\begin{bmatrix} \dot{\mathbf{x}}_1(t) \\ \dot{\mathbf{x}}_2(t) \\ \dots \\ \dot{\mathbf{x}}_M(t) \end{bmatrix} = \underbrace{\begin{bmatrix} A_{11} & A_{12} & \dots & A_{1M} \\ A_{21} & A_{22} & \dots & A_{2M} \\ \dots & \dots & \dots & \dots \\ A_{M1} & A_{M2} & \dots & A_{MM} \end{bmatrix}}_A \cdot \begin{bmatrix} \mathbf{x}_1(t) \\ \mathbf{x}_2(t) \\ \dots \\ \mathbf{x}_M(t) \end{bmatrix} + \begin{bmatrix} \mathbf{B}_1 & & & \\ & \mathbf{B}_2 & & \\ & & \dots & \\ & & & \mathbf{B}_M \end{bmatrix} \cdot \begin{bmatrix} \mathbf{u}_1(t) \\ \mathbf{u}_2(t) \\ \dots \\ \mathbf{u}_M(t) \end{bmatrix} + \tilde{\mathbf{B}}d(t)$$

where for area i : $\mathbf{x}_i(t) \in \mathbb{R}^{N_i \times 1}$ is the vector of states, $\mathbf{u}_i(t) \in \mathbb{R}^{P_i \times 1}$ is the vector of control inputs, and $d(t)$ is the scalar disturbance input. The PMU measurements of voltage, phase angle, frequency and currents at different buses in these areas are accordingly denoted as $y(t) = Cx(t)$. Obviously, if any output feedback control of the form $u = -Ky$ needs to be implemented in a distributed way, for example using *distributed* Model Predictive Control (MPC), PMU data from one area will need to be communicated to actuators in other areas as indicated by the non-zero entries of K . Each of these feedback streams will include an end-to-end delay encountered during transmission through GENI. We will classify these delays into three types - namely, (1) small delays τ_s if the feedback measurements are communicated from PMUs located very close to a given controller, (2) medium delays τ_m if the measurements are communicated from PMUs from more distant buses but still within the operating region of the same utility company, and finally (3) large delays τ_l if the measurements are communicated over a SDN from remote buses that belong to a different company. But the important point to understand here is that if the communication is executed over a shared network then a significant part of τ_s , τ_m and τ_l will include delays from scheduling and routing. We first state the details of our proposed distributed-MPC (DMPC) control algorithm:

Step 1: Local State Estimation - The first step of DMPC is to run a local phasor state estimator in discrete-time with gain L_i at the control center of every i^{th} area, exchanging outputs

with its neighboring areas \mathcal{N}_i as:

$$\begin{aligned} \hat{x}_i(k+1) = & A_{ii}\hat{x}_i(k) + B_{ii}u_i(k) \\ & + \sum_{l \in \mathcal{N}_i} [A_{il}\hat{x}_l(k) + B_{il}u_l(k)] \\ & + L_i(k)[y_i(k) - C_{ii}\hat{x}_i(k)] \end{aligned} \quad (5)$$

Step 2: Prediction of State/Output Estimates - Real-time optimal control requires estimates of the states and outputs over the entire prediction horizon from time $t+1$ until time $t+N_p$, and can only make these predictions based on information up to and including the current time t . Equation (5) will be used to obtain $\hat{x}_i(k+1)$, and optimal estimates can be obtained by forwarding the time index from k to $k+j$ where $j = 1, \dots, N_p$.

Step 3: State Trajectory Communication - The calculated state trajectories will then be sent to the control agents of the neighboring areas via *inter-area* communication, while those of the same area, but from the previous iteration, are broadcast to the controllers via *intra-area* communication.

Step 4: Solve Global Optimization Problem - At each iteration, an objective function will be minimized to solve for the optimal input trajectory. This objective function can be any arbitrary nonlinear function of all the states and the inputs, representing a system-level stability or performance metric, and can be of the form:

$$J_i = \sum_{j=1}^{N_p-1} \left[\hat{x}_{i(1:m)}^{cT}(k+j) Q \hat{x}_{i(1:m)}^c(k+j) + u_{i(1:m)}^{cT}(k+j) R u_{i(1:m)}^c(k+j) \right] \quad (6)$$

Step 5: Input Trajectory Communication - Calculated optimal input trajectories will be communicated and exchanged with neighboring areas.

Step 6: Check Convergence and Repeat - Whether or not to proceed to the next iteration is determined by the convergence of the objective function to its minimum value, achieved via appropriate numerical algorithms such as interior-point methods.

Steps 3 and 5 involve inter-area communication, and therefore will be subjected to the three types of delays τ_s , τ_m and τ_l . We next propose the final step of the design by which the steps 1-5 can be adapted to be *aware* of these delays, instead of being simply *tolerant*.

Step 7: Delay-Aware Control Design The next question is - how can the controller in Steps 1-5 be co-designed with the information about τ_s , τ_m and τ_l . The conventional approach is to hold the controller update until all the messages arrive at the end of the cycle. However, this approach usually results in poor closed-loop performance. Our alternative approach, therefore, is to (1) *design* the time-slots τ_1 , τ_2 , etc. for protocols 1, 2 and 3, and (2) then update the control input as new information arrives instead of waiting till the end of the cycle. If tweaking the protocols is difficult, then an alternative strategy will

be to estimate the upper bounds for the delays using real-time calculus [65]. The approach is referred to as *arbitration*, which is an emerging topic of interest in network control systems [66], [67], and has been recently applied to power systems [68]. Based on the execution of the three protocols, one can define two modes for the delays - namely, *nominal* and *overrun*. If the messages meet their intended deadlines, we will denote them as nominal. If they do not arrive by that deadline, we will refer to them as overruns. Defining two parameters τ_{th1} and τ_{th2} such that $\tau_{th1} \leq \tau_{th2}$, we will define nominal, skip, and abort cases as:

- If the message has a delay less than τ_{th1} , we consider the message as the nominal message of the system and no overrun strategy will be activated.
- If the message suffers a delay greater than τ_{th1} and less than τ_{th2} , the message will be computed; however, the computations of the following message will be skipped.
- If the message suffers a delay greater than τ_{th2} , the computations of the message will be aborted, and the message is dropped. This strategy is motivated by assuming that the messages will be significantly delayed, and are no longer useful.

Accordingly, a feasible way to formulate our execution rules can be: (1) if $\tau_{th1} \leq \tau_{th2} \leq \tau_{wcet}$, where τ_{wcet} is the worst case delay of the system, both abort and skip can happen, (2) **Abort Only**: if $\tau_{th1} = \tau_{th2} < \tau_{wcet}$, the message will be dropped if they miss their first deadline, and (3) **Skip Only**: if $\tau_{th1} \leq \tau_{wcet}$ and $\tau_{th2} \geq \tau_{wcet}$. One idea will be to set $\tau_{th2} = \tau_{wcet}$ to develop a constructive strategy to determine τ_{th1} .

2) *Loop 2: Software Defined Networking (SDN)*: Typically, the Internet cannot provide the required latency and packet loss performance under high PMU data-rate. Moreover, the network performance is highly random, and therefore, difficult to model accurately. With the recent revolution in networking technology, SDN opens up significantly more degrees of freedom in programability and virtualization, especially for the type of controller proposed in Loop 1 [64]. Accordingly, one may next want to design a lightweight framework of next-generation Gigabit communication systems for PMU data transfer and management, compatible with the requirements of Loop 1. More specifically, one may use SDN to virtualize and actively control those networks that constitute the communication system between PMUs and cloud service providers. Such virtualization will permit us to prioritize incidents, and make fast response to the delay requirements imposed by Steps 3, 5 and 7 of Loop 1 in a timely and effective way with minimal communication delay.

In our recent paper [47] we showed how probabilistic network-traffic models in the Internet can be integrated with estimation loops for power system monitoring [69]. The basic idea behind Loop 2 is similar. It will enhance priority-type resource provisioning for the prioritized selection of multiple applications running in the network in parallel to wide-area control. Depending on network traffic, many of these applications may even be non-power related. The end-to-end network provisioning for wide-area control services can then

be formulated as the following optimization problem:

$$\min \sum_{r=1,2,\dots,R} \sum_{j=1,2,\dots,m} p_j^{(r)} c_j^{(r)} \quad (7)$$

constrained to the end-to-end QoS constraints of multiple services (e.g., latency requirements), where m is the total number of network switches managed by SDN controllers and R is the number of types of network services including power grid services. In (7), $p_j^{(r)}$ is the portion of network resources allocated to service r in switch j associated with a cost $c_j^{(r)}$ for ensuring the end-to-end QoS guarantee of all power grid services. Due to the dynamic nature of networks, the end-to-end QoS constraints may be characterized through stochastic models. The main goal of Loop 2 is to solve the optimization problem (7) continuously with changing network traffic, and thereby minimize the delays in inter-VM communication in Steps 3 and 5 of Loop 1. The solution to this provisioning problem will, in fact, lay a foundation for network flow placement. Since SDN provides a logically centralized global view of network resources, the solution for flow replacement will be suitable to be implemented in an SDN controller.

3) *Loop 3: Event-driven Decision Making in the Network*: This is slowest control loop among the three, whose purpose is to track the network traffic condition and the performance of the two outer loops, and thereby take intermittent, and on-the-fly decisions about

- 1) Which PMU data-streams should be assigned to which virtual machine (VM) inside GENI depending on the workload of the VM's at any time while Loop 1 is running, in case a VM suddenly becomes overloaded from other applications,
- 2) Which PMU data-streams should be assigned to which VM's depending on the physical structure of the power system in question, and the resulting correlation between its state variables, and finally
- 3) Which VM (or, equivalently PDC) should talk to which other VM's or PDC's, i.e., the communication topology between the PDC's to execute Steps 3 and 5 of Loop 1.

The idea would be to start from a nominal PMU-PDC assignment structure and a nominal PDC-PDC communication topology, and make intermittent changes to these configurations in case the performance of Loop 1 and 2 falls for any reason at any point of time while they are running. One may accomplish this requirement by constructing and reconfiguring a SDN overlay network. In addition to this *virtual SDN* requirement, there are other network functions that are needed to address the real time performance, monitoring, and security concerns. For example, load balancing among tens or hundreds of PMU data-feeds to a PDC, wide-area throughput acceleration of UDP or TCP flows, intrusion detection or security preachment monitoring, may become important for executing Loops 1 and 2. Extra network functions are needed to handle the IEEE C37.118 and IEC 61850 protocols. More specifically to this application, emerging network function virtualization (NFV) technology provides a good cloud software based solution [70], in which a network function chain can be dynamically provisioned and managed in the form of VMs

or containers. One may explore a "SDN+NFV" approach that uses SDN to actively steer traffic along the NFV chains in the cloud, especially experimental studies on the impact of different NFV chaining strategies on the end-to-end latency.

VII. CONCLUSIONS

This paper addresses infrastructure CPS, that denote the analysis and design of smart infrastructures that monitor themselves, communicate, and most importantly self-govern. We presented three different foundations, (i) Human Empowerment, (ii) Transactive Control, and (iii) Resilience. We also presented two examples of infrastructure, one on the interdependent natural gas and electricity infrastructures, and the second drawn from the nexus between power and communication infrastructure both of which have been investigated extensively of late, and are emerging to be apt illustrations of Infrastructure CPS.

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