On a Control Architecture for Future Electric Energy Systems

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Abstract—This paper presents considerations towards a control architecture for future electric energy systems driven by massive changes resulting from the societal goals of decarbonization and electrification. A historical perspective is provided on the role that architecture and abstractions have played in other technological systems such as the Internet, serial computation, and communication systems. For power systems, we present a viewpoint of architecture as the organization of multiple control loops aligned with the entities involved, as well as taking advantage of time-scale and spatial scale separations. New requirements and challenges in designing the set of control loops required for future electric energy systems are substantiated from a temporal and spatial perspective. Finally, we articulate key desirable control loops that can enable decarbonization of the electricity sector. We thereby argue that the present architecture of electric power grids designed in a different era is indeed extensible to allow the incorporation of increased renewables.

I. INTRODUCTION

Electric grids around the world are undergoing massive changes. At the heart of these changes is the need to decarbonize the electricity sector by replacing fossil fuels with renewables or other carbon-free energy resources. This in turn drives several other changes. Unlike fossil fuels, solar/wind power generation cannot be increased when needed. Hence power consumption may need to be reduced on occasion when solar/wind power reduces. How such reduction can be induced on the part of energy consumers poses challenges. One possibility is through pricing, which itself raises, on the one hand, issues concerning elasticity of consumers, informing consumers of real-time prices, taking account of human behavior, and, on the other hand, of sensing what devices are on/off, consuming how much power, how they can be controlled, the loss of privacy when individual consumer information is communicated elsewhere, etc. It also entails a greater role for storage, to provide a buffer between generation and consumption. Such storage can be in batteries, by pumping water to higher levels, or even in the form of heat in buildings. At the same time, technologies such as power electronics offer many additional possibilities such as grid-forming capabilities that would allow for provision of essential grid support with much less rotating mass in the power system. Controlling all these complex next-generation interactions requires an examination of the important issue of the control architecture of future power systems [1]. Addressing this central architectural challenge is the goal of this paper.

Architecture, and accompanying abstractions, are important for the design of systems [2]. In different systems the architectural solutions are different. For the Internet, the solution has been a “layered architecture,” which has been greatly responsible for its proliferation. The link layer provides the abstraction of a link, the network layer provides a path from one node to another over multiple links, and the transport layer provides the abstraction of a pipe between any two nodes. Each layer simply defines a clear task, and the protocol designer only has to fulfill that task. In serial computation, it is the “von Neumann bridge” [3] separating hardware and software that has been the key to its success. In communications, it is the separation between source coding and channel coding. In many control systems, it is the “separation between estimation and control” that has greatly simplified design [4].

In power systems it has been its control architecture that has provided reliable delivery of power in spite of many uncertainties and disruptions at several levels. Power systems are enormously complex. They involve phenomena spanning time scales ranging from microseconds (e.g., for power electronics switching), to milliseconds (e.g., for electromagnetic phenomena), to seconds (e.g., for electromechanical phenomena governing spinning generators), to minutes (e.g., for dispatch of generators), to hours (e.g., for startup/shutdown of generators), to years (e.g., for installation of new transmission lines). Disruptions happen at all times scales - lightning strikes, failure of equipment, changes in customer loads, changes in weather that affect demand, diurnal and seasonal changes in both demand and renewables, gas pipeline disruptions, etc. Similarly, there is constant change in phenomena spanning an extremely wide spatial scale, from individual households in small neighborhoods interconnected by a distribution feeder line to massive power plants connected by transmission lines traversing hundreds of miles. Nevertheless power systems have provided a reliable electricity supply, i.e., the desired amount of power that each user needs and with associated variables (such as voltage, frequency, power factor, harmonic distortion) that define power quality being within tolerance limits from
their nominal values. This success is fundamentally due to the multiple control loops forming the control architecture that regulate all the electrical variables in spite of all the uncertainties and disturbances.

In this respect, the problems faced by power systems are similar to the problem of homeostasis in biology, where variables like oxygen level, electrolyte balance, temperature, etc., have to be properly regulated in spite of massive changes caused by running, fasting, or pregnancy.

The basis underpinning the control architecture in power systems is the separation of temporal and spatial scales. This separation has clarified the tasks that control loops at several time and spatial scales have to support. Successful design methodologies at each time-scale and spatial scale have been designed, which, when composed together, have resulted in a very reliable overall system. The control loops have also been so designed that there are no unintended adverse interactions between different control loops. Moreover, importantly, the responsibilities for the different control loops have been appropriately assigned and aligned with the economic arrangements of all the entities involved – generation, transmission and distribution companies, consumers, etc. This has led to an efficient and reliable electric energy system. This existing architecture is briefly described in Section II.

The resulting design methodologies have allowed the physical system to grow in size. Indeed, it is the motivation to meet the high standard set by power systems that has led to the galvanizing slogan “plug and play” used in other technological domains. Moreover, the architecture has also allowed the evolution of improved control loop design methodologies over time [5]. The evolution of voltage control from regional-based to inter-regional coordinated is a very good example of how control loop design methodology has changed over time under the control architecture of spatial and temporal separation [6], [7]. This development of voltage control across large-scale power systems bear similarities with the development of TCP/IP protocols for the Internet.

Power systems are however in a massive ferment as the planet moves to sustainable energy systems. Leading this ferment is the shift from fossil fuels to renewable energy sources such as solar and wind power, besides more traditional renewable sources such as hydro. Unlike fossil fuel power plants, as demand increases, wind/solar power cannot be increased as needed – it is not “dispatchable”. Thus the balance between generation and consumption will have to be maintained by adjusting consumption. One way to try to achieve this could be through pricing. That raises many issues such as the uncertainty in how humans react to price changes, assuming that they are even exposed to and aware of price changes. Other possibilities could be direct control of consumer consumption through, say, controlling their air conditioners/heaters, but that requires sensing of customer side variables, which involves issues such as privacy, as well as novel contracts with consumers. Buildings account for a large portion of energy consumption, and therefore shaping their consumption to match renewable generation is essential. There is also the massive transformation in transportation electrification, which imposes huge loads on neighborhood distribution
transformers, as well as variability. Also, as individual homes are equipped with solar roof panels, power generation will become distributed as well as highly variable. How to maintain a reliable electricity supply come rain or shine is a major challenge.

On the other hand, there are new technologies such as phasor measurement units that allow measurement of phase with high precision providing precise situational awareness of power flows. There is also the still untapped potential of power electronics devices in providing control at a finer temporal granularity. There is also increasing deployment of smart meters at customers’ homes that will allow more complex pricing, e.g., time-of-use [8] or EnergyCoupon [9] as well allow privacy constrained data gathering in real-time for more intelligent control. However, with these new technologies comes the challenge of security of the massive cyber-physical system, as information from sensors can be distorted by malicious agents.

How can the aforesaid revolutionary changes be accommodated in electric energy systems? That is the challenge addressed in this paper. Our thoughts in this regard are guided by the following requirements. First, the changes made to the existing control architecture to accommodate increasing renewables must continue to deliver electric power reliably and efficiently in spite of increased variability. Second, the control architecture must be well aligned with all the old as well as the new business entities that are emerging, such as aggregators. Third, any changes will need to be backward compatible in view of the tremendous existing investment in infrastructure. Last, but not least, the design of the architecture should continue to allow room for innovation and not stifle it. With these goals in mind we propose additions to the existing control architecture in Sections V and VI. Where possible, our preference has been to allow distributed decision making in order to foster creativity “at the edge,” in Internet parlance. However, in some cases, such as gas-grid and electric-grid operation we do not hesitate to suggest greater coordination.

This paper presents the grid architecture as a collection of control loops among key entities in the power grids. As is shown in Figure 1 the entities in the grid include independent system operators (ISOs), fuel (gas) suppliers, generation companies (GENCOs) or virtual power plants (VPPs), aggregators, distribution companies (DISCOs), transmission companies (TRANCOs), transportation components, i.e., electric vehicles (EVs) and EV charging stations (EVCSSs), and electricity end users, i.e., customers. The interactions among different entities are identified in Figure 1 where the existing control loops are indicated by solid arrows, while the new control loops to incorporate increased renewables are indicated by dashed arrows. The latter represent research opportunities for the future grid, which are elaborated on in Section IV.

There are several references that discuss the design of power grid architectures [10]-[16]. Dy Liacco [10] introduced a state-transition viewpoint of power transmission system operation which underpins the Energy Management System of modern bulk power grids. Wu et al. [11] review the architectures of control centers in modern power systems and envision a distributed architecture of control centers. References [12], [13] and [14] introduce a GRIP (Grid with Intelligent Periphery) architecture where power grid operation is decomposed into hierarchically structured clusters that include transmission grids, distribution grids, microgrids, and smart homes. Reference [15] identifies three dimensions that can assess and describe the grid evolution given the drivers of change in electric energy systems. Reference [16] reviews the past and present power grids, and points out key technologies that are needed to be developed for supporting the operation of future transmission systems. As the existing efforts on grid architecture design suggest, there is still a need for a holistic architecture that reflects the roles of key stakeholders in both power transmission and distribution systems.

The remainder of this paper is organized as follows. We first describe the present control architecture in Section II as summarized in Figure 1. Section III elaborates the drivers of change that are happening in the electric energy systems. In Section IV we summarize the key research challenges on designing a control architecture for the evolving power grid with increased renewables. Sections V and VI describe the new control loops in transmission and distribution systems, respectively. Section VII provides some concluding remarks.

II. THE PRESENT ARCHITECTURE OF ELECTRIC ENERGY SYSTEMS

Before embarking on what are the future challenges, we begin by describing entities involved, and the current architecture of power systems. Given the complexity of the system, there are multiple perspectives of the architecture. One elucidates the entities involved in transmission and distribution, and the planning and operational aspects involved. Another perspective is through the lens of temporal and spatial scales. Finally, and most important functionally, is to understand the set of control loops that achieve reliable and efficient power delivery, and how they are organized.

We begin with the description of the entities involved.

A. Entities in Transmission/Distribution Grids

- Generation companies (GENCOs) or virtual power plants (VPPs): A GENCO is a company that owns/operates an electric power plant. A VPP is a collection of decentralized power resources (including generation units, storage or demand response) that are controlled via software and can mimic a traditional power plant.
- Distribution Companies (DISCOs): These are responsible for the supply of electricity to consumers.
- Transmission Companies (TRANCOs): These are the entities that own/operate the high-voltage transmission grid.
- Independent System Operators (ISOs): These are independent organizations that coordinate the generation and transmission of electricity across large geographic areas.
- Fuel (gas) Suppliers: This is the group of entities from which the fossil fuel generators purchase their fuel. For the case of natural gas this could be a producer, a local distribution company or a marketer.
• Customers (retail): These are the end users of electricity at the distribution level.
• Aggregators: An electric aggregator acts as an agent on behalf of a collection of customers\(^1\) for the purpose of negotiating the rate with an electric supplier.
• Transportation: This category covers components of the transportation infrastructure that interact with the electric grid, and include electric vehicles (EVs) and EV charging stations (EVCSs).

B. The Temporal and Spatial Scales

Dy Liacco\(^2\) pioneered the state transition diagram of control areas, as illustrated in Figure 2. This, together with the development of singular perturbation techniques\(^3\), provided the architectural and theoretical justification of spatial and temporal scale separation (shown in Figure 3). It led to the development of a suite of decision-support tools such as steady-state analysis, small-signal dynamic security assessment, and large-signal transient stability assessment.

The physics of the electric grid combined with the controls results in a wide ranging set of dynamics across multiple temporal scales, which are as follows:

1) At the fastest time-scale, of the order of microseconds, we have power electronics switching.
2) Then we have the order of milliseconds, for the electromagnetic transient dynamics.
3) Next come electro-mechanical dynamics, of the order of seconds, typically associated with large rotating machines like synchronous generators.
4) Then we have the scale of power balancing between generation and consumption which ranges from minutes to days, and which spans frequency regulation, dispatch and commitment actions.
5) Power system restoration is the process of returning grid equipment to normal service following an outage. Depending on the severity of the damage, restoration time can take hours or days.
6) Finally at the slowest time-scale of years or decades is where decisions on capacity adequacy are made.

Traditionally these problems have been treated separately under an assumption that the control loops in the faster time scale will be sufficient to achieve steady-state from the perspective of the slower time-scale, thereby simplifying the problem.

Likewise, there has also been a separation of spatial scales, as follows:

1) The regional, i.e., transmission systems.
2) The local, i.e., distribution systems.

These spatial scales are operated somewhat separately although they are physically coupled. For example, when making decisions about the delivery of bulk electricity from generating stations to load centers, the local voltage control issues are not directly considered. Hence, for instance, the market mechanisms at the transmission level can be modified without considering the specifics of the distribution system devices.

In the next subsection we elaborate on the operational and planning aspects in transmission and distribution systems.

C. Transmission/Distribution Grids: Planning and Operation

Transmission System Planning: Transmission systems in the US are planned on a regional basis with the aim of meeting future demand and maintaining grid reliability as the fleet of generating resources and their locations continues to evolve. In some areas Regional Transmission Organizations (RTOs) conduct the transmission planning process\(^2\). Transmission owners are predominantly compensated for their investments in the transmission network via cost-based rates. Building transmission infrastructure is a complicated and slow process, with concerns being raised that the process may not be able to accommodate the needs of large-scale renewable integration. The best renewable resource areas are often in more remote locations where the electric transmission infrastructure is weak\(^2\).

Transmission System Operations: The ISO is responsible for running the wholesale market into which GENCOS (Loop 4) and DISCOs (Loop 8) submit their offers and bids for power, respectively. The wholesale market run by the ISO consists of two stages: the day-ahead market and the real-time market. In turn the GENCOS are responsible for procuring fuel (Loop 1) for fulfilling the schedules determined by the ISO. The ISO has to take into consideration several other issues including how to ensure reliable delivery of power in the event of disruptions aka contingencies. The ISO also has a number of other functions needed for the reliable operation of the transmission level grid, including administering products for energy, ancillary services, capacity and financial transmission rights. The ISO also coordinates with the TRANCOs on transmission system outage scheduling and planning (Loop 3). The TRANCOs are responsible for maintenance of transmission equipment (Loop 5). In non-ISO areas the vertically integrated electric companies continue to be responsible for both transmission and distribution system operations.

\(^1\)Aggregators may not possess physical assets for generating and storing electric energy, whereas the VPPs typically own physical assets.

\(^2\)The terms RTO and ISO are often used interchangeably.

\(^3\)The Control Loops are numbered and shown in Figure 4 and described in Section II-D.


D. The Hierarchy of Control Loops in the Present Architecture

The present architecture of power systems includes a well-defined hierarchy of controls, many automatic and others manual, in order to ensure the system stays in the normal operating condition or returns quickly to the normal state when disrupted.

The stable operation of alternating current based power systems requires the monitoring and control of several key variables. In addition to real and reactive power, the main variables that need to be controlled include voltage, frequency and the phase angle of voltage. Further at the distribution level power factor and harmonics are also important.

Some DISCOs generate their own power (particularly in the vertically integrated paradigm), or purchase power from other entities via power purchase agreements, or from a wholesale electricity market.

Electric distribution companies (utilities) undertake a comprehensive process to develop Integrated Resource Plans (IRPs) to ensure that there is an adequate portfolio of supply-side and demand-side resources to meet the peak demand and energy needs of their customers at least cost, typically over a 10-20 year planning horizon. Resource planning requirements differ from state to state in the US. The plans account for a variety of risks including load growth, fuel prices, fuel diversity and emissions, and require the involvement of state public utility commissions (PUCs) along with other stakeholders. Thereby, societal choices are introduced into the planning of the grid infrastructure, for example, through state renewable portfolio standards.

Distribution System Operations: Many DISCOs use Supervisory Control and Data Acquisition (SCADA) systems for ensuring the correct operation of substation equipment, through data acquisition, monitoring and control of the distribution system (Loop 10). SCADA combines hardware, software and communications to monitor various equipment, send control signals and perform key operations such as voltage control, load balancing, power quality monitoring, fault protection etc. The first layer in this is the hardware that actuates and monitors the system conditions, including reclosers, capacitor controls, voltage regulators, fault current indicators etc. The second layer does the data collection, communication and control through remote terminal units (RTUs) and intelligent electronic devices (IEDs). The third layer is responsible for communications with the host platform typically in the control center. The fourth layer is the software platform that integrates the multiple data streams, analyses it and provides the capabilities for display and interaction to the human operators.

Today most intelligence at the distribution level is in substations with limited control and visibility downstream through devices such as reclosers, customer smart meters, etc. In the future more intelligence is likely to be deployed behind the customer meters via EV software, smart thermostats, home energy storage systems, etc.

A few of the control loops at the transmission level are as follows:

- Automatic Voltage Regulators: Generators are equipped with Automatic Voltage Regulators (AVRs) which detect the terminal voltage, compare it with the reference voltage and then regulate the excitation system of the generator to cancel out the difference (or error). This is a local and automatic control action (Loop 4).

- Frequency Control: The first frequency control loop (aka primary or droop) is the automatic action by Governors (Loop 4) which sense the local frequency deviations and respond immediately to try and arrest the frequency change within seconds by changing the speed of the synchronous generator. Next comes the secondary frequency control (Loop 2), also called Automatic Generation Control (AGC), which ensures that frequency is brought back to the nominal value within minutes. This is done in a shared fashion by all participating generators via changing the references of the speed governors, and is coordinated centrally by the System Operator.

- Economic Dispatch: While governor and AGC actions may be adequate to return the system to normal frequency, the result may not be economically optimal. The System Operator solves an optimization problem, leading to “economic dispatch” which minimizes the cost of balancing generation and load, subject to various constraints such as resource and line limits. This Economic Dispatch is part of Loop 2, and in the real-time market is typically conducted every 5 minutes. The ISO considers the generation offers, forecasts of demands and other inputs in the calculations, and clears the market resulting in prices and dispatch targets for generators. The generators then adjust their outputs so as to meet the targets provided by the ISO.

- Unit Commitment: The System Operator solves an optimization problem to determine the schedules of generators in order to meet the day-ahead demand at least cost and yet respect the physical limits of the generators as well as transmission constraints. Unit Commitment also forms a part of Loop 2. In some cases Operators may also make out-of-market decisions to turn on units in order to maintain system reliability.

- Outage Scheduling: System Operators coordinate maintenance schedules for both generators and transmission lines (Loops 2 and 3 respectively), weeks or months in advance in order to ensure adequate capacity will be available to meet anticipated demand, and that healthy levels of resource margins are maintained for ensuring reliability despite adverse events.
been increasingly integrated at the transmission level. This is where decisions on building new plants (Loops 2 and 4) or transmission lines (Loops 3 and 5) are made.

A few of the control loops at the distribution level are as follows:

- Power Quality/Reliability: DISCOs perform a number of control actions on the distribution grid components in order to provide reliable power to Customers (Loop 6). These include circuit reconfiguration, power factor correction, feeder load balancing, etc.
- Power Purchases: In order to provide adequate power to their Customers, DISCOs may participate in wholesale electricity markets operated by the ISOs (Loop 8).
- Demand Response: Aggregators may offer demand response services, i.e., offering to reduce or increase demand, in ISO markets on behalf of multiple customers (Loop 9).
- Electricity Billing: If a region has no electricity retail market, a DISCO can charge customers for their electricity usage (Loops 6 and 7). In a region with a retail market, aggregators charge customers based on the rate in the contracts that their customers choose (Loops 12 and 13). The aggregators also need to pay their local DISCO for the power delivery services provided by the DISCO (Loop 11).

Additionally, there are a number of other control or switching actions that may be undertaken to protect key equipment from abnormal conditions such as faults, over-voltage, overheating, abnormal frequencies etc.

The development of the control laws and their implementation in software has allowed for the building of the largest human-made engineering system of the 20th century, namely the electrical grid.

II. THE DRIVERS OF CHANGE

While the present architecture of the electric energy system has served the electricity industry well over the decades, we anticipate a major paradigm shift in the way electricity gets generated, delivered, and consumed. This is driven by the societal choice of decarbonization which will have two major ramifications on the electricity sector, first, a substantial number of generating units will be replaced by renewable energy resources. Second, there will be a substantial amount of new load, a prime example being the electrification of transportation [20, 21]. When generation becomes uncontrollable, as in the case of renewables, the balance between generation and demand will need to be maintained by incorporating storage to buffer imbalances between the two, and by changes in how demand is managed or controlled. The key drivers of changes among different entities are shown in Figure 5. Next we elaborate on these key drivers.

A. Integration of Variable Renewable Energy

Over the past two decades wind and solar resources have been increasingly integrated at the transmission level. The inherent variability of these resources presents new challenges to the operation of the grid. Reliable grid operation will need more operational flexibility to balance the intermittent renewable generation. One example of the challenges posed by renewables is illustrated by the now infamous “Duck Curve” in California [22, 23], where the net load is low in the middle of the day since solar production is at its highest and then rises rapidly towards the evening peak as demand increases and sunlight fades. This results in the need to ramp the generation fleet by a significant amount over a span of just a few hours, posing a major challenge.

B. Aggregation of DERs in Wholesale Markets

While historically the spatial separation has resulted in the distribution system being characterized as purely load from the transmission level perspective, the paradigm has begun to change to one where transmission and distribution system operations will become more integrated. A key reason behind this is the increasing deployment of distributed energy resources (DERs).

In 2020 the Federal Energy Regulatory Commission (FERC) issued Order 2222 to allow aggregations of DERs to participate in wholesale electricity markets [24]. This will allow DERs to provide energy, ancillary services (such as frequency regulation and contingency reserves) and capacity, and compete in wholesale markets with large generators. This order permits Aggregators to pool multiple small DERs so as to meet minimum size thresholds and other requirements of the ISOs. The current participation models, market clearing algorithms and other mechanisms will need to be modified in order to account for the suite of technologies that might be included in DERs, including electric storage, distributed generation, demand response, energy efficiency, thermal storage and electric vehicles. Currently only two ISOs in the US, namely New York (NYISO) and California (CAISO) have DER aggregation programs.

At present, ISOs do not have visibility into the distribution grid, but this could be a concern when large numbers of DERs start participating in the wholesale market via Aggregators. When the DER Aggregator tries to maximize its profit in the wholesale markets it will have an impact on the operation of the distribution grid. It is important to ensure that the participation of DERs in the wholesale market does not violate any of the distribution system constraints. Thus, there is a need for a coordination framework to exchange information and control signals between the Aggregator, the DISCO and the ISO.

Researchers are looking into the question of whether there is a need for a new entity of “Distribution System Operator” (DSO) to coordinate retail transactions and operations, analogous to the way the ISO coordinates these at the wholesale level. A distribution level market may be able to account for distribution constraints (such as voltage and line flow limits) and provide appropriate price signals through distributed locational marginal prices (dLMPs) [25]. For instance, Andrianesis and Caramanis [26] presents an approach to consider the impact of DER scheduling on distribution transformer degradation.
Fig. 4. The existing control loops in current power systems
C. Electric Vehicles

One of the largest sources of emissions is the transportation sector. Hence a transition from the internal combustion engine to electric vehicles is necessary (but not sufficient) for achieving decarbonization goals. To accomplish these there is a need for significant investments in EV charging infrastructure. Further, uncontrolled charging of EVs could result in serious challenges as the peak demand could far outstrip what the distribution equipment is rated for [27].

D. Energy Storage

Historically the grid has operated largely on a just-in-time principle where electricity generation attempts to balance load on a second-by-second basis. Hence Energy Storage technologies could be important to effectively integrating intermittent renewables into the grid. Pumped Hydroelectric Storage (PHS) currently makes up 96% of worldwide energy storage capacity [28]. Other technologies include batteries, molten salt (thermal storage), compressed air and flywheels. Energy storage can provide a number of benefits to the grid including capacity firming, peak demand management, ancillary services and transmission and distribution upgrade deferral. However, there are a number of challenges with regards to scaling these solutions. For instance, with PHS there are only a few locations where the reservoirs can be located. For other technologies, such as batteries, the capital costs are still quite high [29]. Further, there are sustainability issues as the mining of lithium for lithium-ion (Li-ion) batteries has serious environmental impact.

E. Demand Response

Demand response involves the modification of energy usage by reducing or shifting it in time in order to better match the supply. This could be in the form of direct load control where utilities can cycle appliances such as air-conditioners and water heaters in exchange for a financial incentive in order to manage peak demand. Another approach to elicit customer participation via financial incentives is to provide them with time-based rates. These include time-of-use pricing, critical peak pricing, variable peak pricing, real time pricing, and critical peak rebates. Smart meters are a key enabling technology for such programs. Time-of-use rates could be the key to managing the increased peak demand arising due to the charging needs of Electric Vehicles [27].

F. Microgrids

Microgrids are local grids which can be formed by connecting a group of loads and distributed energy resources, and which can disconnect from the traditional grid to operate autonomously. They are useful for serving remote areas, or when the main grid suffers disruptions such as due to storms. Hence microgrids may help to improve grid resilience. In the future electric energy systems, microgrids may be used more widely, particularly as the deployment of DERs and grid-edge intelligence increases.

G. Power Electronics

A number of the newer energy technologies such as solar panels, wind generators and batteries interface with the grid via power electronics inverters. As we transition away from a grid with large synchronous generators towards one with such inverter-based resources (IBRs) there will be a number of challenges, particularly since those synchronous machines have provided much of the control actions (both frequency and voltage) needed to maintain grid stability. One key challenge will be managing the grid with lower inertia, since the lack of inertia will impact grid stability. There is a need to research alternative methods known as grid-forming controls which can exploit the capabilities of the IBRs [30].

H. Advanced Sensors and Communication

Over the past few decades a number of smart grid technologies have begun to be deployed that provide improved capabilities to manage the grid through more granular measurements (both spatial and temporal), communications and intelligent controls. A few examples of these include:

1) Advanced sensors known as Phasor Measurement Units (PMUs) that allow operators to assess transmission grid stability.

2) Sensors that measure transmission line capacity in real time thereby enabling dynamic line rating changes.

3) Smart sensor technologies at distribution level, such as fault circuit indicators (FCIs), that give greater visibility and control below the substation.

These new sensors, together with new communication capabilities such as 5G, offer opportunities for designing new control loops around the future electric energy systems to achieve higher reliability and efficiency.

IV. RESEARCH OPPORTUNITIES AND CHALLENGES OF CONTROL ARCHITECTURE IN FUTURE POWER GRIDS

Addressing all the challenges raised by incorporating the new entities as well as the new capabilities described above poses several fundamental challenges from operations to planning, and from transmission to distribution systems, for the electric energy sector. Any architectural changes will need to satisfy several objectives:

1) They continue to satisfy the primary objective of providing reliable, efficient, and low-carbon electricity.

2) They are well aligned with the responsibilities and interests of all the new and old entities.
3) The new mechanisms are backward compatible in view of the massive current investment in infrastructure.
4) They do not constrain future innovation, but encourage it (a la the layered architecture of the Internet).

**Research Challenges:**

- **R1:** What is an architectural design for operating networked microgrids, and for designing protocols that allow for plug-and-play with security certificate?
- **R2:** How to control and operate energy storage devices across transmission and distribution systems with deep penetration of variable resources?
- **R3:** What are the control protocols that could incorporate massive amounts of inverter-based resources (e.g., wind, solar, and EV charging) into the existing electric grid at scale?
- **R4:** What kinds of security guarantee can be given in the presence of many smart controllers and sensors across the electric grid?
- **R5:** What is a coordinated scheduling and planning framework that would allow for deep penetration of vehicle electrification?
- **R6:** What are new utility business models and rate structures to incentivize innovation and investments in grid-edge technologies?
- **R7:** What are appropriate market mechanisms to dispatch massive amounts of uncertain resources with a priori risk awareness?
- **R8:** How to manage a multi-energy system with stronger coupling between gas and electricity?

In outlining an architecture for the future electric energy system, we have adopted a design philosophy that decisions should be delegated to the lowest, i.e., most local, level that is appropriate. This is motivated by the consideration of spurring innovation at the edge. However, where necessary we advocate higher level coordination. As an example, we suggest a tighter and high level integrated joint design of the gas network and the electric grid, as opposed to current distributed decision making.

Building upon these new technologies as well as the design philosophy, we outline additions to the control architecture of the electric grid that would allow for large scale integration of renewables, but would still be backward compatible. We present several new control loops at the transmission and distribution levels in the next two sections, respectively.

**V. NEW LOOPS IN FUTURE TRANSMISSION SYSTEMS**

Given the technological innovations and societal objectives of decarbonization and electrification, the control architecture of the future electric energy systems will need to be adapted to best accommodate the needs. These new control loops range from integrating individual resources to resource-grid coordination and to cross-infrastructure coordination. We present some of the new control loops in the following subsections.

**A. Inverter-based Resources Control**

Inverters are the power electronics devices that can convert direct current (DC) to alternating current (AC) electricity. They are becoming key equipment since a number of Distributed Generation (DG) technologies such as solar, wind power and batteries need to convert DC electricity to AC in order to connect to the bulk power system. Figure 7 shows a DC energy resource connected to the grid at a point of common coupling (PCC) via an inverter and a low-pass filter. The inverter is regulated by a feedback controller that observes the inverter terminal voltage and current, and tunes the inverter modulation index, in order to track a given setpoint. Almost all inverters currently connected to the grid are grid-following inverters. The setpoints for the grid-following controller are real and reactive power which can be determined by solving the optimal power flow (OPF) problem [31]–[33]. A phase lock loop (PLL), a current controller, and a Pulse Width Modulation (PWM) module are three typical functional blocks in a grid-following controller [34]. The grid-following inverter is designed for the situation where the frequency and voltage magnitude at the PCC are in a nominal range. This type of inverter cannot provide a nominal frequency and a voltage magnitude at the PCC autonomously without a well-established grid. As a result, the grid-following inverter alone cannot form an autonomous power grid in the restoration stages. This motivates the development of a new type of controller called *grid-forming controller* which is described next.

Grid-forming inverters can regulate terminal voltage magnitude and frequency at the PCC by tracking the frequency and voltage setpoints, and can provide restoration support [30], [34]. Grid-forming controllers can be broken down into three categories [30]: 1) droop controllers [35], 2) synchronverter controllers [36], [37], and 3) virtual oscillator controllers [38]. Since there is a tight coupling between grid frequencies (voltage magnitudes) and real (reactive power) power in a power grid with small line loss, the *droop controllers* stabilize grid frequencies (voltage magnitudes) by changing real (reactive) power that DGs inject into the grid [35], [39]. They can also determine how much real and reactive power each DG contributes in order to eliminate real and reactive power imbalance. A droop controller typically consists of a power controller, a voltage controller, current controller, and a PWM module [34], [35]. A *synchronverter controller* enables an inverter to mimic the behavior of a synchronous machine [36], [37]. Such a control strategy is motivated by the fact that the contemporary grid apparatus, e.g., protection and control, is designed for a grid where synchronous generators are dominant. Engineering an inverter-based resource that behaves like a synchronous generator makes it easier for it to be integrated into an existing power grid, since its host grid does not require many changes. Another attractive feature of the synchronverters is that they can provide their host grid with inertia, which makes the grid less sensitive to disturbances. A *virtual oscillator controller* is programmed such that the controlled inverter can mimic a limit-cycle oscillator that can be synchronized with other inverters. The parameter tuning procedure of a virtual oscillator controller can be achieved in a systematic way [38].

There are decades of experience in operating the grid with large synchronous generators, with well-developed control
Fig. 6. New control loops for future electric energy systems with deepened renewable energy penetration

Fig. 7. A grid-connected inverter with a controller at the grid interface

loops (discussed in Section IID) based on well understood models and interactions. However, as we transition to a grid dominated by IBRs, we lack the experience and body of research to operate the grid reliably. The key control challenges include inertia, frequency regulation, voltage control, fault protection schemes, black start and wide-area coordination. It is also important to recognize that in many systems there will be a period of transition where both the conventional and new resources will have to operate in coordination.

B. Cyber-Physical Security of Control Loops

The decision making in operation of bulk power systems heavily relies on massive distributed measurements. For example, the electricity market operation is built upon a wide-area state estimator that takes SCADA data as inputs. The AGC changes the setpoints of generators based on the SCADA measurements that may be thousands of miles away from the control center where the AGC is located. Due to the tight dependence of operational decisions on measurements, there arises a concern that a malicious adversary may compromise the grid operation by manipulating the physically distributed, poorly-secured sensors. Reference [40] envisions a scenario where an attacker can be benefited financially by deliberately tampering with the SCADA measurements. Reference [41] suggests that the grid can be destabilized by an attacker who intrudes into the frequency/tie-line flow measurements of the AGC system. Moreover, as the scale of IBRs grows, so does the need for communication in order to monitor and control them. Thus increasingly the inverters might become targets for cyber attacks. An attacker might use an inverter’s software as an entry point for a malware attack that could spread to the rest of the grid and cause cascading failures. Thus there is a need for certification standards and programs that can help the industry to manage the cybersecurity risks [42].

One challenge of designing a cybersecurity solution is how to distinguish cyber attacks from physical disturbances. For example, some cybersecurity solutions (e.g., [41]) are based on power grid models that are only valid around certain operating conditions. However, large disturbances, e.g., line tripping, might drive the grid to an operating condition where the model used for the cyber solutions is not valid anymore, thereby triggering false alarms. Besides, distinguishing cyber and physical anomalies is important because different types of anomalies require different mitigation actions. Therefore, to avoid false alarms due to physical anomalies, an anomaly classification procedure is necessary for developing cybersecurity solutions. While a substantial body of literature is devoted to address the cyber-physical security of power grids [43]–[46], the deployment of cyber-physical security solutions in real-world power systems is still in a nascent stage. Recently, the dynamic watermarking method [47] has been used to detect malicious attacks on the sensors in prototypical microgrids [34], and tested via simulation on attacks on the AGC loop [41] (See Figure 8). Without guarantees on cyber-physical security, new technologies that leverage wide-area measurements will not find acceptance for real-time grid operations.
As the costs of storage technologies continue to decrease, the potential of energy storage in all aspects of the grid from planning to operations. Already we are seeing tremendous interest from developers in terms of the generation queues of ISOs where battery storage is combined with other technologies (usually solar) to form Hybrid Power Plants.

D. Gas and Electric Coordination

With the retirement of a number of coal generators and the overall penetration of renewables still being low, the electrical grid in the US has begun to rely more on gas fired generation. Hence the coordination of gas and electricity resources is taking on a greater importance in the reliable operation of the electricity system. The pipeline operators and electrical generator operators need to coordinate to minimize natural gas pipeline outages during peak electric demand periods and prioritize supply to generators during cold weather when the load tends to be high due to heating needs. Further, the increase in renewables may lead to additional strain on natural gas infrastructure to deal with ramping due to their variability.

Currently the gas and electric systems are modeled and optimized separately. Co-optimization of the electricity and natural gas operations could be more efficient than separate optimizations. To improve reliability more information sharing and improved modeling capabilities are needed. In particular, as system dynamics become more important, steady-state models may not be sufficient to address the challenges.

E. Risk-aware Dispatch and Scheduling

Unit commitment (UC) and economic dispatch (ED) are two key problems that ISOs must solve in order to maintain the steady-state reliable operation of the electric grid while ensuring lowest cost for the customers. Some generators require on the order of hours to start-up or shut-down, hence the “unit commitment problem” of determining the schedule for the availability of different generators, is typically done one day in advance. Also, generators submit their offers on an hour-by-hour basis for the next day, and the System Operator decides on which bids to accept to meet aggregated demand bids, based on lowest cost, i.e., day-ahead economic dispatch. Further, on the given day, generators are economically dispatched, typically, on a 5-minute basis, so that the System Operator can balance generation and supply, i.e., real-time economic dispatch. Currently these problems are formulated as deterministic optimization problems. To manage uncertainties ISOs use reserve requirements and procure headroom capacity across all their commitment and dispatch processes. However, these requirements are relatively static and do not vary dynamically depending on the immediate system needs. As the uncertainties grow in both scale and complexity due to a variety of factors such as the increased penetration of variable renewables, more frequent severe weather events and the emergence of DERs, the traditional deterministic approach may result in an excessive need for such reserve capacity with associated increased inefficiency. Hence there is a need for approaches that explicitly consider risk and manage the large number of uncertainty scenarios optimally.

A number of approaches have been studied to deal with the increasing uncertainty in power systems. These include...
stochastic optimization [57], [58], robust optimization [59], [60], chance constrained optimization [61], and the scenario approach-based optimization [62]–[65]. The software, hardware, and modeling techniques used by the ISOs will need to be improved in order to handle both the massive increase in computational complexity as well as the variety of new generation technologies that will emerge. While a variety of approaches are possible, it is clear that there needs to be better control of the increased uncertainties that will be present in the future.

VI. NEW LOOPS IN FUTURE DISTRIBUTION SYSTEMS

This section proposes several new control loops in future distribution systems. The large-scale penetration of DERs in distribution systems adds unprecedented operational complexity which may require the distribution systems to shift towards a microgrid-based architecture. This constitutes a move towards a less centralized and more distributed design and operation of distribution systems. Transportation electrification introduces interdependence among utilities, aggregators, and EVs and their charging stations. The increasing interdependence would in turn imply a more coupled control architecture where the temporal and spatial scale separation will need to be evaluated more adaptively. Grid edge intelligence (e.g., smart meters, and IoTs) enables customers to play a significant part in enhancing grid operation efficiency. Further, the heterogeneous nature of load and the decreasing amount of energy transactions over distribution lines motivate changes to the business models of utilities. The above aspects can be addressed by introducing some new control loops into future distribution systems.

A. Microgrid-based Distribution Systems

This subsection introduces the self loops at the Customer block and the loops between the DISCO blocks and the Customers block in Figure 6. These new loops are motivated by the increasing penetration of DERs in the distribution grids, and they are enabled by the emerging computation and communication capacities at the grid edges. We first present a physical architecture of future distribution systems that is fundamentally different from today’s distribution grids; then we present a hierarchical control scheme that manages the physical architecture; and we finally present tools that can be leveraged to analyze the security of the microgrid-based distribution system.

1) Physical Architecture of a Microgrid-based Distribution System: The increasing penetration of DERs poses significant challenges for distribution system operation. A future distribution system may contain hundreds to thousands of DERs (e.g., rooftop solar panels, and energy storage). The key challenge for DISCOs is how to manage such a massive deployment of DERs. One possible physical architecture for a future distribution system able to manage massive DERs is shown in Figure 9. The grid edge components, i.e., loads, DERs, and energy storage, are clustered into several groups, and each group of edge components is served by a small-scale, autonomous power system, i.e., a microgrid. Each microgrid is managed by its own management system (µMS). With such a configuration, the DISCO only needs to manage several µMSs, instead of controlling massive DERs. As a result, the operational complexity for the DISCO is significantly reduced. The resilience of the distribution system to natural disasters can also be greatly enhanced by a microgrid-based configuration. Each microgrid can either connect to the main grid or disconnect from the main grid and operate autonomously. Were a natural disaster to occur that caused the host distribution networks to lose their power delivery function, then each microgrid could proactively disconnect from its host grid and supply its load autonomously. Thereby, large-scale blackouts can be avoided.

Fig. 9. Physical architecture of a microgrid-based distribution system

2) Microgrid Hierarchical Control: The DERs, load, and energy storage within a microgrid are managed hierarchically. Taking an AC microgrid as an example, one may consider a hierarchical microgrid control scheme including device-level, secondary, and tertiary control. The device-level control of inverters, as in Section V-A, can stabilize the frequency and voltage magnitudes in a decentralized manner. In order to recover the frequency and voltage magnitudes to their nominal values, a secondary control is needed. Figure 10 shows a centralized secondary controller in a microgrid. The secondary controller aims to regulate the voltage magnitude and frequency at some critical microgrid nodes by tuning the setpoints of the grid-forming inverters. The setpoints of the secondary controller are given by the tertiary controller when the microgrid is in a grid-connected mode, and they are determined by the microgrid itself when it is in an islanded mode. It is worth noting that the secondary controller can be implemented in a decentralized or distributed manner [66]–[70]. The tertiary control regulates the real and reactive power flow between the microgrid and its host distribution system. The setpoints of the tertiary control are provided by the distribution system operators [33], [71], and they are tracked by tuning the setpoints of the secondary controller. It should be noted that the control architecture is highly dependent on the communication infrastructure that allows for information exchange between each individual DER and the µMS, and between each µMS and the DISCO.

In order to make sure the controllers in a microgrid are well configured, it is critical for system planners and operators to establish the stability of a microgrid distribution system, under disturbances such as operational mode changes (e.g., one microgrid disconnects from its host grid), DERs’ on/off
status changes, and topology changes (e.g., line tripping). Simulation studies to investigate stability require small time steps of numerical integration due to the fast dynamics of IBRs, and so speeding up simulation is critical \[72\]–\[74\]. A drawback of simulation-based methods is that they cannot rigorously establish stability, as only a finite set of disturbances are considered. On the other hand, analytical methods require a Lyapunov function to rigorously certify an equilibrium point’s stability \[75\]–\[78\], which is generally challenging \[79\]–\[81\]. Recently, machine-learning techniques have been used to construct Lyapunov functions \[81\]. The general limitation of existing analytical methods is that they typically use simplified models of inverter dynamics, e.g., \[81\], and moreover require knowledge of the dynamics of all DERs in the microgrid, which is not easily available.

While microgrids appear to be very promising, there is limited experience about other services within microgrids, such as black-start without connecting to the main grid. Further, the above only discusses the stability of a microgrid-based distribution system. It is worth noting that the cybersecurity issues in the microgrid context are equally important, since the microgrid entails many control loops. Perhaps methods used for addressing the cybersecurity issues in transmission systems, e.g., the watermarking approach \[41\], can be migrated to distribution systems.

B. New Loops for Transportation Electrification

Transportation electrification requires new control loops for the coordination of EV charging and discharging. Aggregators and EVs participate in this loop. There is also the slower time-scale of planning required to determine EV charging station placement, in which DISCOs and EV charging stations participate.

1) Coordination of EV Charging and Discharging: A large-scale deployment of EVs introduces both opportunities and challenges for distribution grid operation. On the one hand, the batteries of EVs can be used to provide grid services, such as optimizing load profiles, if they are well coordinated. On the other hand, simulation-based studies \[82\], \[83\] have shown that uncoordinated EV charging may jeopardize a distribution grid’s security by incurring large line losses and large voltage deviations \[82\], and by decreasing the lifespan of grid equipment, such as transformers. In today’s distribution systems, there is very limited coordination of EV charging and discharging. For the future grid, we envision that EV chargers will have the capability to communicate with an aggregator, and that there exist contractual agreements between EV owners and the aggregator that allow the aggregator to control the charging rates of the EV chargers within a scheduling horizon, e.g., 24 hours, taking into account the requirements on availability and state of charge (SOC) specified by individual EV owners. The aggregator may seek to minimize the line loss of the distribution system, to fill the valley of a load profile, or to establish a tradeoff between costs of energy and battery degradation \[82\], \[84\]–\[87\].

2) EV Charging Station Placement: The adoption of EVs will need widespread charging infrastructure to be developed, at different charging levels, and for a variety of transportation needs ranging from local commutes to inter-city travel to commercial transportation. Sufficient deployment of charging infrastructure is a prerequisite for large-scale deployment of EVs. A natural question is how to efficiently deploy EV charging stations in a distribution power system. This problem is termed as the EV charging station placement problem which aims to determine the locations and capacities of the EV charging stations.

Currently there is little coordination of the electric and transportation infrastructures for EV charging station (EVCS) placement. This is a major area of research opportunities for the future grids with massive numbers of EVs. For the EVCS placement problem, EVCS planners aim to determine the sites and capacity of EVCSs. The problem can be formulated into an optimization problem with an objective function that reflects the costs of EVCS construction, distribution system expansion, voltage regulation, etc. The constraints are related to EV charging demand in the area under study, including power distribution network limits, and budget limits. A large body of literature is devoted to coordinating the electric and transportation infrastructure by considering various practical factors \[88\]–\[92\].

C. Demand Response

The objective of conventional power grid operation is to make generation track load, since fossil-fuel generators are dispatchable, while loads are traditionally not considered as finely controllable. In the future grid, large-scale integration of renewables would render the generation side less dispatchable, but intelligence at the grid edges, such as smart meters and Internet of Things (IoTs), enhance load controllability \[93\]. This enables the load to track the generation. Demand response programs make it possible to unlock the flexibility at the load side in order to maintain load-generation balance. Demand response (DR) programs are designed for changing customers’ electricity usage patterns \[94\]. DR programs can be categorized into 1) price response and 2) direct load control \[93\]. The price response approach changes the electricity usage patterns by using price signals or other incentives. Examples of price response include market-index retail plans designed by utilities, time-of-use \[8\], critical peak pricing \[8\], and coupon-based programs \[9\]. To illustrate the basic mechanism of price response, we take the coupon-based programs \[9\] as
Hence many traditional consumers could become prosumers, which will lead to the growth of distributed energy resources (DERs).

D. New Business Model for Utilities with Prosumers

Significantly.

To this end, one possible mechanism is where the aggregator can leverage a coupon-based demand response program \[9\]. The aggregator first predicts electricity price several hours ahead, say, 2-hours ahead, and checks whether the price forecast exceeds a threshold. If yes, the aggregator can inform its customers via mobile phone applications that they will obtain a certain number of lottery tickets if they can decrease electricity usage by a certain amount within a given period of time. The number of lottery tickets issued to a customer can be based on the price forecast and energy saving behavior of the customer \[9\].

Direct load control requires aggregators (or load serving entities, LSEs) to change the setpoints of customers’ equipment, e.g., air conditioners \[95\], refrigerators, and swimming pool pumps \[96\]. As an example, reference \[95\] proposes a two-layer direct load control strategy which is shown in Figure 11. Suppose that the aggregator can control the setpoints of many air conditioners. In the first layer, given a planning horizon, an aggregator participates in the wholesale electricity market and determines an optimal power consumption trajectory over the planning horizon with an objective of minimizing costs from purchasing energy in the wholesale market. Once the optimal power consumption trajectory is determined, the second layer can change the setpoint of each AC in order to drive the total power consumption to track the optimal power consumption trajectory, while making sure that the comfort temperature for each individual home is maintained.

The adoption of both direct load control and time-varying rates is currently in a nascent stage despite many pilot programs tested by a number of utilities. As grid-edge technologies proliferate the potential for such programs could increase significantly.

VII. Concluding Remarks

Finally, we come back to the issue of extensibility, by which is meant an important property of a design that allows the future incorporation of new capabilities or functionalities. The power system architecture of the present was designed to have the important properties of a reliable and efficient system, such as fault tolerance, scalability, stability, etc. The question before us today is whether the original design is also extensible to allow for large penetration of renewables along with other compensatory strategies on the demand and storage side. This paper provides constructive suggestions towards achieving this goal at several levels, and thereby argues that the current design is indeed extensible. Specifically, we have articulated several new control loops for the future electric energy systems aimed at achieving the new societal goals of decarbonization and electrification of transportation.

We now describe some new research challenges from the viewpoint of architecture design. The first challenge is how to balance the pragmatic view of a system in with large sunk investment, with a greenfield view of the system. The architecture of the electric energy system has evolved over the past century with many loops of control, communication, and computing technologies intertwined with the physical system. Thus the challenge is how to design new control loops that are backward compatible with existing loops.

The second challenge is how to provide a coherent viewpoint of this complex system across multiple temporal and spatial scales, with some formal verification or some form of guarantees of performance. The assumptions of time-scale and spatial-scale separation will need to be mathematically revisited with the increasing level of complexity involved with this system, particularly in light of new distributed energy technologies and intelligence at the grid-edge.

A third challenge is how to translate these control loop innovations into practical implementation. Many of the innovations of architectural design will need to be blended with rapid prototyping, trials and errors, and feedback design. Such intermediate efforts between research and implementation will need to be facilitated to more effectively and nimbly adapt to the changing nature of the complex energy systems.
The fourth challenge is how to provide architectural design principles towards a dynamically changing societal objective. As of now the pivotal concern of the electric energy system is how to decarbonize and how to provide resilient electricity services. However, societal needs and objectives may further change over a long course of time. Architecture design will need to be revisited and adapted accordingly at a longer time scale trajectory.

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