

The Need for Holistic Enterprise Control Assessment Methods for the Future Electricity Grid

Amro M. Farid, Bo Jiang, Aramazd Muzhikyan, and Kamal Youcef-Toumi

Abstract—Recently, the academic and industrial literature has coalesced around an enhanced vision of the electric power grid that is responsive, dynamic, adaptive and flexible. As driven by decarbonization, reliability, transportation electrification, consumer participation and deregulation, this future grid will undergo technical, economic and regulatory changes to bring about the incorporation of renewable energy and incentivized demand side management and control. As a result, the power grid will experience fundamental changes in its physical system structure and behavior that will consequently require enhanced and integrated control, automation, and IT-driven management functions in what is called enterprise control. While these requirements will open a plethora of opportunities for new control technologies, many of these solutions are largely overlapping in function. Their overall contribution to holistic techno-economic control objectives and their underlying dynamic properties are less than clear. Piece-meal integration and a lack of coordinated assessment could bring about costly-overbuilt solutions or even worse unintended reliability consequences. This work, thus, reviews these existing trends in the power grid evolution. It then motivates the need for holistic methods of integrated assessment that manage the diversity of control solutions against their many competing objectives and contrasts these requirements to existing variable energy resource integration studies. The work concludes with a holistic framework for “enterprise control” assessment of the future power grid and suggests directions for future work.

I. INTRODUCTION

Traditional power systems have often been built on the basis of an electrical energy value chain which consists of a relatively few, centralized and actively controlled thermal power generation facilities which serve a relatively large number of distributed, passive electrical loads [1], [2]. Furthermore, the dominant operating paradigm and goal for these operators and utilities was to always serve the consumer demanded load with maximum reliability at whatever the production cost [3]. Over the years, system operators and utilities have improved their methods to achieve this task [4], [5]. Generation dispatch, reserve management and automatic control has matured. Load forecasting techniques have advanced significantly to bring

forecasts errors to as low as a couple of percent and system securities and their associated standards have evolved equally. It does not appear, however, that this status quo is set to last.

Instead, multiple drivers are set to dramatically change the basic assumptions upon which the electrical power grid was built [6]. The first of these is decarbonization [7]. The European Union, for example, has committed to reduce greenhouse gas emissions in the power sector to 1990 level by 2050 [8]. Such targets create a strong pressure for renewable energy penetration in both the transmission as well as the distribution system [9]. Next, electricity demand continues to grow sometimes as fast as 10% per year in the quickly developing economies [10], [11]. Such demands motivate the need for “peak shaving” and load shifting capabilities so as to avoid the installation of new power generation capacity and maximize the capacity factor of already existing units [3], [12]–[16]. Decarbonization drivers also dramatically affect the transportation sector and the emerging consensus is that both public and private transport should be increasingly electrified so as to improve well-to-wheel efficiencies [17]–[19]. This transportation electrification driver requires the electrical grid to be fit for a new, significant and previously un-envisioned purpose [20]–[24]. Next, the trends towards electric power deregulation that began at the turn of the century are likely to continue in the hope of achieving greater social welfare and improved electricity price and service [25]–[34]. Finally, these deregulation trends have inspired and empowered consumers who respond to both physical and economic grid conditions [3], [12]–[16]. In short, these five drivers require the steadily increasing penetration of solar and wind generation as well as evolving capabilities to support demand side management for the tremendous diversity of loads that connect to the electrical grid.

The integration of these three new grid technologies of renewable energy, electric vehicles, and demand side resources ultimately imposes fundamental changes to the grid structure and behavior. As a result, the already existing suite of control technologies and strategies are set to dramatically expand in both number and type. While existing regulatory codes and standards will continue to apply [35]–[37], it is less than clear how the holistic behavior of the grid will change or how reliability will be assured. Furthermore, it is important to assess the degree to which control, automation, and information technology are truly necessary to achieve the desired level of reliability – if indeed it can be accurately quantified. Thirdly, it is unclear what value for cost these technical integration decisions can bring. From a societal perspective, smart grid initiatives have been priced at several tens of billions of dollars

Amro M. Farid: Thayer School of Engineering, Dartmouth College, 14 Engineering Drive, Hanover NH 03755. Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue Cambridge, MA 02139, USA. Email: amfarid@dartmouth.edu, amfarid@mit.edu

Bo Jiang: Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue Cambridge, MA 02139, USA. Email: bojiang@mit.edu

Aramazd Muzhikyan: Engineering Systems and Management, Masdar Institute of Science and Technology, PO Box 54224, Abu Dhabi, UAE. Email: amuzhikyan@masdar.ac.ae

Kamal Youcef-Toumi: Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue Cambridge, MA 02139, USA. Email: youcef@mit.edu

in multiple regions [38], [39]. Therefore, there is a need to thoughtfully quantify and evaluate the steps taken in such a large scale technological migration of the existing power grid.

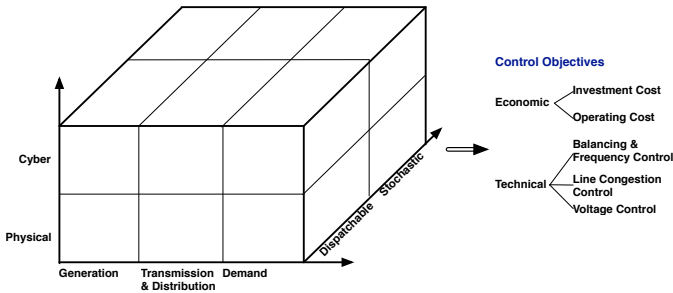


Fig. 1. Guiding Structure of Argument. The power grid is taken as a cyber-physical system composed of an energy value-chain with dispatchable and stochastic elements that must fulfill certain technical and economic control objectives.

This work, thus, argues that a future electricity grid with a high penetration of renewable energy and demand side management technologies requires holistic assessment methods for the profile of newly adopted energy and control technologies. This argument is fashioned as shown in Figure 1. On one axis, the electrical power grid is viewed as a *cyber-physical* system. That is, assessing the physical integration of renewable energy and demand side resources *must* be taken in the context of the control, automation, and information technologies that would be added to mitigate and coordinate their effects. On another, it is an energy value chain spanning generation and demand. On the third axis, it contains dispatchable as well as stochastic energy resources. These axes holistically define the scope of the power grid system which must meet competing *techno-economic* objectives. Power grid technical objectives are often viewed as balancing operations, line congestion management and voltage management. Economically speaking, the investment decision for a given technology; be it renewable energy, demand side resources or their associated control must be assessed against the changes in reliability and operational cost. These economic and control technical will later be viewed from the lens of dynamic properties including dispatchability, flexibility, forecast ability, stability, and resilience. Naturally, such holistic assessment methods will represent an evolution of existing methods. This work thus seeks to draw from the trends and recommendations in the existing literature and frame them within the structure of Figure 1.

Consequently, the paper is similarly structured. Section II describes the evolution of the physical power grid in terms of the integration of variable energy resources and the subsequent changes in grid structure and behavior. Next, Section III moves up to the “cyber-layer” and reviews potential new control technologies and how they may be used to support enhanced operations. Next, Section IV turns to discussing the many techno-economic objectives that the power grid must meet. It discusses the potential adequacy of existing assessment methods – drawing heavily on a methodological review of the state of the art in renewable energy integration studies. Section V then proposes a holistic framework for “enterprise control” assessment of the future power grid. Section VI concludes with the potential for new directions of active research and

development.

II. EVOLUTION OF THE PHYSICAL POWER GRID

The emergence of new drivers in the power grid is likely to bring about an evolution of the physical power grid. This motivates fundamental changes in electrical power generation and consumption patterns, such as integration of variable energy resources (VER), electrification of transportation and introduction of demand-side management (DSM) techniques. As a result, the overall structure and dynamics of the system is set to evolve; potentially invalidating several traditional assumptions about power grid behavior. This section investigates these drivers for change and the likely evolution to the physical power grid’s structure and dynamics that they will cause.

A. Drivers for the Evolution of the Power Grid

Since the power grid’s inception more than a century ago, a number of fundamental assumptions have driven its structure and operation. Since then, the power grid has received a number of incremental upgrades in generation efficiency, operating procedures, and system security. However, this status quo is set to change as new drivers come into effect. This section specifically addresses five new drivers: grid decarbonization, reliability concerns, transportation electrification, implementation of demand side management and changes in market design and regulatory paradigm [6].

Decarbonization has become the main driver of the power grid evolution as a result of increasing concerns about greenhouse gas emissions and climate change. The Europe Union, for example, is targeting to reduce greenhouse gas emissions to 80% – 95% of the 1990 level by 2050 [8]. In the future, the choice of energy sources is likely to be constrained by environmental considerations and rather than technological limitations and resource scarcity. The European Union Emissions Trading scheme has imposed a price for carbon credits for power generation facilities [9], [40]. If this trend continues, the cost of CO_2 emissions can become one of the factors affecting generation capacity investment decisions. This trend incentivizes renewable energy sources (RES) over coal and natural gas powered generation units. RES have a number of advantages over traditional energy sources: environmental friendliness, no danger of their depletion over time (sustainable energy sources), and no fuel expense requirements [41]. The first interest towards renewable energy sources emerged after the oil crisis in 1970s, leading to some investments in their technological development [42]. However, after the decline of oil and gas prices during 1980s, interest in renewable energy sources faded. Currently, the installation of renewable energy sources, particularly of wind energy, is taking hold as they are supported by governmental mandates and regulatory foundations such as Renewable Portfolio Standards [43], [44].

Power grid reliability enhancement is the second driver. Currently, most of the U.S. electrical power infrastructure planning and operation aspects are supported by computer simulations to ensure system reliability. However, many parts of the system are over 25-30 years old and have been built prior to the

emergence of extensive computer and communication networks, which raises questions about power grid reliability [45]. The disparity between electricity demand and electric power infrastructure growth makes the North American electricity infrastructure increasingly stressed, and further aggravates reliability concerns. Figure 2 contains power system outage data from US Energy Information Administration (EIA) and the North American Electric Reliability Corporation (NERC). Both sources show that there is a growing tendency of power system failure probability [6]. Worldwide, the last decade has seen 5 blackouts affecting more than 50 million people: (US-Northeast 2003, Italy 2003, Brazil/Paraguay 2009, Java/Bali 2005, and India 2012).

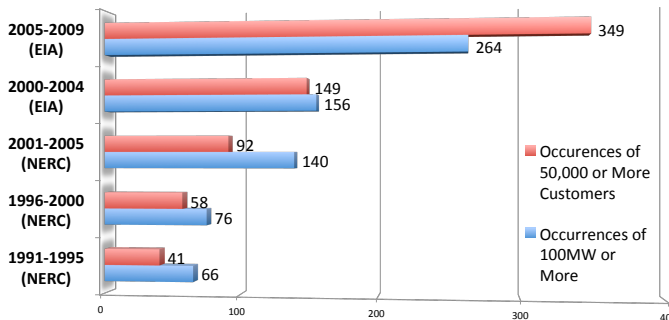


Fig. 2. U.S. Electric power outages over 100MW and affecting over 50,000 consumers (1991-2005) (Data courtesy of NERC's Disturbance Analysis Working Group Database) [6]

Decarbonization has led to the third driver: namely transportation electrification. The American transportation sector accounts for approximately two-third of the U.S. fossil fuel demand [11]. Without viable alternatives to the oil, increasing energy demand will continue to rely mostly on fossil fuel resources. Alternatively, EV's are nearly twice as energy efficient as vehicles with internal combustion engine and have no emissions *at the point of use*. From a technological perspective, electrical vehicles (EV) have reached maturity thanks to active investments by major automobile manufacturers [46], although its market will take time to develop [47], [48]. Despite the decarbonization advantages, the electrification of transport increases the dependence on the electricity grid [20]–[23]. Advanced controls, together with existing innovation in power electronics and energy storage, are enablers to simultaneously manage the operation of the grid and the electrical transportation system [20], [22]. Compared to independent operations by the power grid and transportation sectors, collaborative control strategies can achieve a series of benefits, solving some issues faced by both groups [22]. For example, the availability of decentralized storage onboard transportation units can allow the use of the transportation system as a complex demand-response system in what is commonly known as vehicle-to-grid applications [49]–[51]. In such a scenario, the transportation system can generate revenue from energy stored during peak-periods. Once transportation elements are able to concurrently and dynamically plan their operations, these future systems will enable reduced overall energy use by the transportation system, as well as provide the ability to accommodate the increased penetration of renewables in the power infrastructure.

Another major driver to the evolution of the power grid is highly enabled and participating electricity consumers. Historically, the power system has operated in the paradigm, that the actively managed power generation supply closely followed passive demand [1]. The power grid was designed and operated on this unilateral basis. The size of the power peak determined the required generation capacity, and sub-daily variability determined the required flexibility [5]. However, the emergence of advanced technologies like smart meters [52]–[55] and power line carriers (PLC) [56] into the grid has facilitated communication with consumers and empowered them to make decisions based on the real-time grid conditions [54], [56]–[59]. These enabling technologies allow demand to migrate from a passive, non-dispatchable behavior to one that is responsive to dynamic prices and reliability signals [14]–[16]. The integration of demand-response technology introduces potentially millions of new consumer-driven dynamical systems each with its own control loop. How the power grid will behave after the full integration of demand-side management is not yet clear, and will largely depend on the implementation details. This can depend on the types of signals that customers receive and where the decisions are made. Some recent work has demonstrated demand side management integration scenarios that cause grid instability and volatility [60]–[62]. Furthermore, those power system operators that have implemented price-responsive demand-side management require complete visibility to energy resources [63]. This practice is unlikely to continue given the shear scale and cost of telemetry and instrumentation.

Power system deregulation is the final driver for the evolution of the power grid. Throughout most of its history, the power system has consisted of vertically integrated utilities, each having monopolies over its own geographical area [28]. Since 1978, this vertically integrated value chain has become increasingly unbundled to allow for diversified and competitive wholesale transactions [25]–[34]. The overwhelming trend has been towards privatization, deregulation, restructuring, and re-regulation. The new regulatory environment with its diversity of market players and associated technologies has resulted in a new energy value chain consisting of five parts: 1) fuel/energy source, 2) power generation, 3) electricity delivery through transmission networks, 4) electricity stepping down into distribution networks, and 5) delivery to end-consumers. Most of the existing focus has been on the supply side but greater attention to the demand side is likely to occur.

These five drivers suggest major changes in the physical power grid in the form of integration of variable energy resources and demand side resources. For the remainder of the work, the discussion of electric vehicles and energy storage resources will be bundled under dispatchable demand side resources.

B. Characteristics of Variable Energy Resources

The five drivers, discussed in the previous section, demonstrate the strong role of variable energy and demand side resources in the future grid. This section addresses the key characteristics of these resources and contrasts them to the conventional generation and demand portfolio.

Past:	Generation/Supply	Load/Demand
Well-Controlled & Dispatchable	Thermal Units: Few, Well-Controlled, Dispatchable	
Stochastic/ Forecasted		Conventional Loads: Slow Moving, Highly Predictable

Fig. 3. Traditional Grid Generation and Demand Portfolio [64]

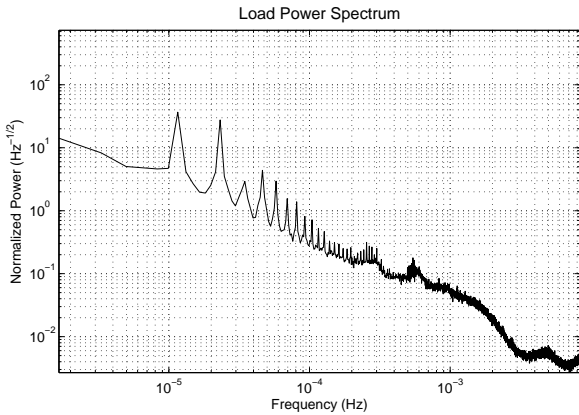


Fig. 4. Normalized power spectrum of daily load (Data from Bonneville Power Administration) [65]

As shown in Figure 3, the power network has traditionally consisted of relatively few, centralized and dispatchable generation units and highly predictable loads [1]. On the demand side, a spectral characterization of a typical load profile is shown in Figure 4. Variations span a wide range of frequencies with slow variations having larger magnitude that correspond to the daily periodicity of the demand. A similar spectrum has been previously reported photovoltaic and wind power generation [67], [68]. These multiple time scales excite and affect the different behavioral phenomena in the power grid shown in Figure 5. The traditional method of satisfying the demand consists primarily of dispatching the centralized generation to load forecasted at the day-ahead and hourly timescales and then allowing automatic feedback control techniques to address the remaining difference [5].

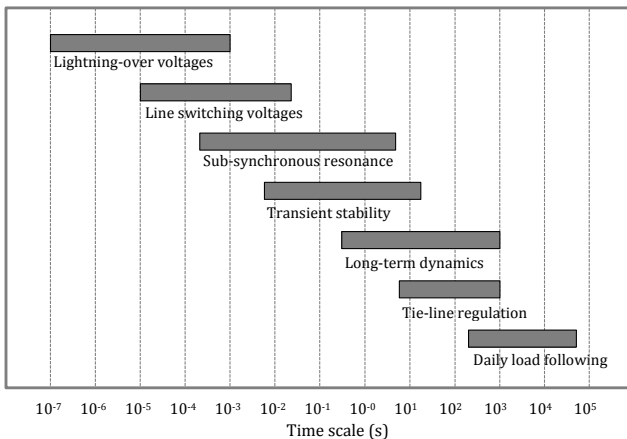


Fig. 5. Time scales of physical power grid dynamics [66]

Over time, load became highly predictable with the state of the art forecast error being approximately 3% [66], [69]. On the supply side, the economic and regulatory structure drove power generation facilities towards economies of scale [70]. Consequently, different types of generation fulfilled different parts of the load: large coal/nuclear power plants supply the base load, combined cycle gas plants follow the changing load, and internal combustion engines and gas turbines come online during the peak load [4]. In summary, Figure 3 demonstrates the clear distinction between generation and demand behaviors in the traditional power system. Generation consists of only dispatchable units and has no stochastic component, while demand is not dispatchable and its forecasted value is used in operations planning. However, the new drivers change the picture of the generation and demand portfolio.

Future:	Generation/Supply	Load/Demand
Well-Controlled & Dispatchable	Thermal Units: (Unsustainable cost & emissions) ↓	Demand Side Management: (Requires new control and market design) ↑
Stochastic/ Forecasted	Renewable Energy Sources: (Can cause unmanaged grid imbalances) ↑	Conventional Loads: ↓ (Growing & needs curtailment)

Fig. 6. Future Grid Generation and Demand Portfolio [64]

The drivers described in the previous section change the picture of the generation and demand portfolio to the more balanced one shown in Figure 6. From the perspective of dispatchability, VERs are non-dispatchable in the traditional sense: the output depends on external conditions and are not controllable by the grid operator [45]; except in a downward direction for curtailment. As VERs displace thermal generation units in the overall generation mix, the overall dispatchability of the generation fleet decreases. On the other hand, the introduction of demand-side resources allows the flexible scheduling of consumption, which raises dispatchability of demand. In spite of this, consumer-level dispatchability may not equate to the same from the grid operator’s perspective. In regards to forecastability, variable energy resources increase the uncertainty level in the system [45]. Relative to traditional load, VER forecast accuracy is low, even in the short term [71]. There are two major groups of wind forecasting techniques: numerical weather prediction (NWP) and statistical methods [72], [73]. The former use more complicated models based on the current weather conditions. This kind of model is mainly used for long term wind forecasts; 24 hours ahead and more. The latter is based upon historical data input and is applied to shorter terms. Moreover and similar to wind generation, the consumption pattern of demand side resources have a stochastic nature from the perspective of power grid operator. In short, Figure 6 demonstrates a grid in which generation and supply are on a much more equal footing. They both have stochastic and dispatchable components and hence should assume similar roles in the power system operation. Naturally, power system assessment techniques should correspondingly evolve to allow for both control as well as disturbance to originate from either generation or demand.

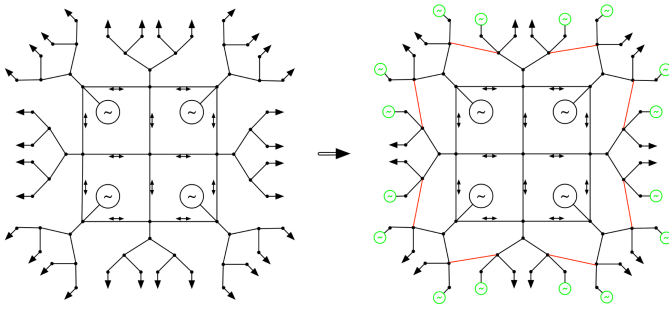


Fig. 7. Graphical Representation of the Evolving Power Grid Structure [64]

C. Changes in Power Grid Structure

In addition to their dispatchability and stochasticity, VER's nature require subsequent changes in the power grid structure; primarily in the distribution system. Traditionally, the power network consists of meshed transmission network, connecting centralized generation units on a wide area, and radial distribution networks, delivering power to the final consumer. This clear separation between transmission and distribution networks allows the study of these two types of networks separately and develop different standards and requirements for each type of network [1]. However, because VERs do not typically have the same technical and economic scale, they break the assumption of centralized generation and allow generation in the distribution system. Figure 7 shows the corresponding evolution of power grid structure as a change in the spatial distribution of generation.

The change in power grid structure has implications on its operation. Distributed generation creates the potential for upstream flow in the distribution system, where it was not generally permitted before [74]–[76]. The protection system has to be redesigned accordingly [75], [77]–[79]. Another challenge is the potential for over-voltages. The mitigation of these challenges may require new stabilizing connection lines within the distribution system; thus turning it into a mesh network of multiple microgrids and potentially effacing the clear separation between transmission and distribution [80]–[84]. Such structural changes create the need for joint study of transmission and distribution networks and suggests that assessment methods develop accordingly.

D. Changes in Power Grid Dynamics

Although the many physical power grid phenomena shown in Figure 5 do overlap [66], traditionally, the power systems literature has treated them strictly separately. This separation is based upon the hierarchical control structure which makes up the “cyber-layer” of Figure 1. It is broken up into a primary, secondary and tertiary control [5], [85]. Primary control addresses transient stability phenomena in the range of approximately 10-0.1Hz [86]–[88]. Generator output adjustments on this timescale are performed by the implementation of local automatic control techniques such as automatic generation control (AGC), and automatic voltage regulators (AVR) [5]. The former responds to fast imbalances between generation and consumption, while the latter responds to changes in generator output voltage [66]. Secondary control, at the minutes

timescale, resides within the operations control center and fixes the set points for these automatic control techniques [4]. It also includes the manual actions of power system operators which assist the automated and semi-automated techniques to secure operations in the fastest possible way [4]. Finally, tertiary control occurs at the time scale of tens of minutes or hours. Often called economic control, it is implemented as the continuous re-dispatch based upon an optimization program that minimizes the total operational cost of the system subject to the appropriate constraints such as generator capacity and line limits [5]. The clear distinction in the time scale of these control has allowed the practical and long-standing assumption that each control technique can be studied independently.

The integration of variable energy resources challenges this assumption and further blurs the distinction between control technique timescale. Recent reviews summarize the impact of VER integration [89]–[92]. A spectral characterization of both wind [67] and solar generation [68] has been conducted to show that VER integration affects *all* time scales of power system operation. In response, the Federal Energy Regulatory Commission (FERC), has recently changed its requirements on minimal re-dispatch frequency from 1 hour to 15 minutes [93]. Individual power system operators have gone even further; with the Pennsylvania-New Jersey-Maryland Independent System Operator (PJM-ISO) dispatching every 5 minutes. Manual operator actions also are facing downward pressure. One recent study in the German-based 50-Hertz Transmission System Operator shows that the increasing penetration of VERs has lead to more frequent manual operator actions – especially in regards to curtailment [94]. In the meantime, the introduction of grid-scale storage [95]–[99], smart buildings [100]–[105], and fast ramping generation facilities [106] expands the scope of dynamic stability studies into slower time scales dominated by dynamic poles in the hydraulic and thermal energy domains. In short, that VER integration introduces new dynamics at *all* time scales suggests that the traditional separation of primary, secondary and tertiary control is increasingly blurred and must be readdressed together. That demand side resources can be, in principle, leveraged at all time scales also blurs these distinctions. Mathematically, the overlapping physical power grid dynamics can be viewed as a *convolution* of behaviors which would necessitate holistic assessment methods.

The introduction of mesh networks (i.e. microgrids) in the distribution system shown in Figure 7 can also bring about new power grid dynamics. This occurs when the power grid is operated in such a way as to have variable rather than static network topology. In such a situation, the continuous-time transient stability dynamics are superimposed on the discrete-event network switching [66]. Such hybrid dynamic systems have an interesting property that while each network topology configuration may be dynamically stable in its own right, the meta-system which allows switching between the configurations may not be so [107]. Furthermore, many of the control theory concepts such as controllability and observability are inadequate for hybrid systems [108]. Therefore, dynamically reconfigured power grids do not just motivate the need for holistic assessment approaches but also represent a rich application area for hybrid control theory contributions.

The promise of such work is resilient [109]–[113], self-healing power grids that respond to disturbances and contingencies [114]–[120]. In contrast, the San Diego Blackout of September 8 2011 is a reminder of the importance of even routine switching decisions [121], [122].

In conclusion, the need for holistic assessment methods is a consequence of the evolution of the physical power grid. As generation and demand continue to evolve to take on balanced and similar roles, each will contribute to the power system operation both from the perspective of control as well as stochastic “disturbance”. Neglecting any of the quadrants in Figure 6 risks either overstating the need for control at extra expense or understating it at the risk of degraded reliability. Additionally, the blurring of the distinction between transmission and distribution suggests distribution can no longer be viewed as a passive participant fulfilled by an active and centralized transmission system operator. Instead, the responsibility of grid operations management must increasingly be distributed across the power value chain. Thirdly, a temporal blurring is occurring as the time scales of primary, secondary, and tertiary power grid control continue to overlap and convolve the power grid response. Finally, hybrid control theory necessitates holistic assessment in cases where the system structure is dynamically switched; in this case to achieve the desirable properties of reconfigurability, self-healing and resilience.

III. ENHANCED POWER GRID ENTERPRISE CONTROL: STRATEGY, PROPERTIES AND TECHNOLOGIES

Returning to the guiding structure provided by Figure 1, the previous section demonstrated a number of evolving trends that will change the nature of the physical power grid. These require a “re-think” of holistic power system control and assessment. This section now addresses the “cyber-layer” found in Figure 1. Rather than adhere to the traditional dichotomy of technical and economic control objectives, this work instead raises the concept of integrated enterprise control [123]–[125] as a strategy for enabling holistic dynamic properties. It then briefly mentions the emerging technologies set to bring about such a strategy.

A. Power Grid Enterprise Control: Strategy

The ongoing evolution of the power grid can already be viewed through the lens of enterprise control. Originally, the concept of enterprise control [123], [124] was developed in the manufacturing sector out of the need for greater agility [126], [127] and flexibility [128]–[130] in response to increased competition, mass-customization and short product life cycles. Automation became viewed as a technology to not just manage the fast dynamics of manufacturing processes but also to integrate [131] that control with business objectives. Over time, a number of integrated enterprise system architectures [132], [133] were developed coalescing in the current ISA-S95 standard [124], [125]. Analogously, recent work on power grids has been proposed to update operation control center architectures [134] and integrate the associated communication architectures [54]. The recent NIST interoperability initiatives

further demonstrate the trend towards integrated and holistic approaches to power grid operation [135]. These initiatives form the foundation for further and more advanced holistic control of the grid [114]–[118].

B. Power Grid Enterprise Control: Dynamic Properties

These integrative initiatives are a fundamental step towards power grid operation that is founded upon the fusion of technical and economic control objectives which enable holistic dynamic properties. Here, five properties are discussed: dispatchability, flexibility, forecastability, stability, and resilience. These dynamic properties correspond to the traditional technical and economic dichotomies shown in Figure 1. However, this work frames the discussion in terms of dynamic properties because they integrate rather than decompose the engineering design of the power grid as a large complex system. Consequently, as the power grid’s physical and cyber layers continue to evolve, it may become more clear how these properties improve or degrade.

	Generation	Demand
Dispatchability	<ul style="list-style-type: none"> Low – Wind, Solar, Run of River Hydro Medium – Hydro, Solar CSP High – Thermal Units 	<ul style="list-style-type: none"> Low – Lighting Medium – HVAC, Commercial buildings High – Industrial production
Flexibility/ Ramping (Thermal Energy to Work ratio)	<ul style="list-style-type: none"> Low – Nuclear & Coal Medium – CCGT High – Hydro, GT, IC 	<ul style="list-style-type: none"> Low – Chemical, petrochemical, metals Medium – HVAC, Commercial Buildings, Refrigerators High – Heaters, kettles, EV battery
Forecastability	<ul style="list-style-type: none"> Low – Solar PV Medium – Wind generation High – All dispatchable generation 	<ul style="list-style-type: none"> Low – N/A Medium – lighting, cooking, hair drying High – Scheduled Industrial Production
Stability	<ul style="list-style-type: none"> Synchronous Generators w/ AVR Wind Induction Generators w/ low voltage ride through Solar PV w/ power electronics 	<ul style="list-style-type: none"> Synchronous motors in HVAC applications Induction Motor appliances with active harmonic control EV’s w/ power electronic based control
Resilience	<ul style="list-style-type: none"> Recovery from generator faults Intentional switching of generators Intentional and Unintentional Switching of Lines 	<ul style="list-style-type: none"> Recovery from load shedding Intentional switching of loads

Fig. 8. Grid Enterprise Control to Enable Holistic Dynamic Properties [64]

To that effect, the future electricity grid, with all of its new supply and demand side resources, must holistically enable its dynamic properties. First, generation and demand are set to take much more equal responsibility over power grid operation. This appears in the degree of forecastability but also in the degree of dispatchability and flexibility. Furthermore, the combination of these three properties suggest a grid that is generally more dynamic in nature, and so requires specific attention to ramping capabilities and dynamic stability. Finally, the transformation of a power grid’s structure from one that is topologically fixed to one that is composed of actively and readily switched microgrids suggests the need for resilience. Figure 8 shows the balanced role of generation and demand in regards to these five dynamic control properties.

Addressed holistically, different components of the power generation and demand have differing levels of dispatchability [136], [137]. While thermal generation has traditionally fulfilled this role, it is likely that electricity-intensive industrial production can serve the counterpart role [138], [139]. A medium level of dispatchability can be achieved with hydro, concentrated solar power and commercial buildings. Finally, wind, solar PV, run-of-river hydro, and lighting have the least dispatchability. This taxonomy of generation and demand

resources effectively introduces a pareto analysis in regards to system dispatchability, which of course is required to cover the stochastic elements in the future grid. More concretely, existing power grids can generally accommodate modest levels of VERs [92] because a certain level of existing dispatchability but if this penetration were to grow the system dispatchability may not be sufficient to meet reliability standards [35], [140].

While dispatchability is a necessary control property, on its own, it is insufficient due to the process limitations of the various generation and demand resources. System flexibility, or resource ramping, needs to be carefully addressed [141]–[143]. Using another pareto analysis, one sees that ramping capabilities are often very much tied to the ratio of stored thermal-fluidic energy to mechanical work. Facilities with a very large ratio such as nuclear, coal, chemicals and metals have relatively low ramping capabilities. In contrast, facilities with a high ratio such as hydroelectric, gas turbines, internal combustion engines, heaters and kettles can easily ramp. The integration of VERs is a challenge not just because of their lack of dispatchability but because the stochastic nature can cause ramps of various *speeds* and not just magnitude [45].

The aggregate dispatchability and flexibility must also be able to meet the lack of forecastability of the stochastic elements on the power grid. The presence of uncertainties decreases the effectiveness of the scheduling process significantly; raising the potential for system imbalances [92], [141]–[143]. Such imbalances create a volatile situation which requires ever-more frequent and costly manual actions [94] in concert with automatic generation control [5]. It is also important to consider that while these errors can compound within the grid, the concept of *geographical-smoothing* can allow for them to also be diminished. As ever more variable energy resources are integrated, positive and negative errors in geographically separate units can ease the needs for dispatchability [144].

As generation and demand begin to contribute equally to power grid operation, they can also make equal contributions to dynamic stability. Traditionally, power system stability is classified into three complementary aspects: frequency, angle, and voltage stability [5], [74], [145]. Variable energy and demand side resources impact each of these differently. Synchronous motors, especially when aggregated into virtual power plants, can come to eventually play similar roles of synchronous generators [86]. The impacts of induction machines in wind generators has received much attention on all types of power system stability [86]. This discussion is set to expand as “smart” induction motor appliances become active entities on the power grid [86]. Finally, DC sources such as solar photovoltaic generation and battery-electric vehicles connected via power electronics [146] have the potential to provide highly reconfigurable approaches to power grid dynamic stability. The inclusion of demand side energy resources is very much inline with recent literature which advocates highly decentralized open-architecture approaches to maintaining stability [147], [148].

Finally, resilience is necessary as the power grid’s structure comes to accept actively and readily switched microgrids. While transient stability studies have often addressed the grid’s

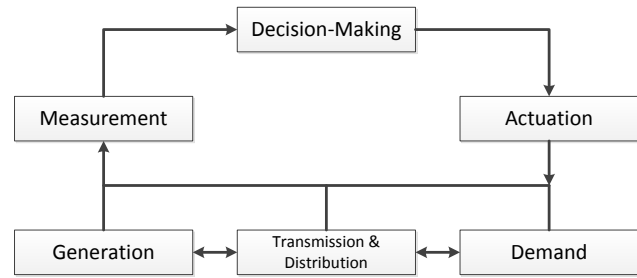


Fig. 9. Integrated Enterprise Control of the Power Grid [64]

survival in response to the failure of a given generator or line [86]–[88], the study of resilience demands the grid to not just recover from a single failure but also be ready for subsequent failures. Furthermore, the strength of the microgrid concept is in the ability to *intentionally and actively* island themselves in response to perturbed conditions elsewhere in the grid [75], [77]–[79]. While some work has addressed the islanding of one microgrid, relatively little work has addressed the operation of multiple microgrids [80], [149]. Such a capability would depend on the mix of connected resources be they on the demand or generation supply of the distribution system.

C. Power Grid Enterprise Control: Technology Integration

The five holistic dynamic properties of dispatchability, flexibility, forecastability, stability and resilience take on greater importance in the context of the vast number of emerging “smart-grid” control technologies entering the market [150]. Individually, these technologies bring their own local function. However, in reality, their value emerges in the context of the full enterprise control loop of measurement, decision-making and actuation shown in Figure 9 [64]. While an in-depth review [150] of these emerging technology offerings is beyond the scope of this work, a cursory mention the leading options serves to further motivate the need for holistic assessment.

These “smart-grid” control technologies are mentioned along the loop of measurement, decision-making and actuation shown in Figure 9. Although the transmissions system continues to introduce new control technology, perhaps the most evident upgrades appear in the distribution system; further blurring the distinction between the two systems. For example, in the measurement and communication infrastructure SCADA [151], as a well-established transmission technology is quickly entering distribution. In complement, smart meters [52]–[55], phasor measurement units [152], and dynamic line ratings [153], [154] have received a great deal of attention in both academia and industry. In decision-making, transmission energy management systems functionality is being repackaged in distribution management systems [155], [156]. An extension of these is facility energy management systems which can integrate to the power grid [102]. Finally, a bloom of actuation devices are set to appear all along the power value chain. Virtual and real generation aggregators are being developed for economics oriented control in both generation and de-

mand [157]–[159]. To that effect, model predictive control techniques [160] have advanced significantly to support both individual as well as groups of facilities, be they for power generation or industrial production. FACTS devices [161] such as static var compensators, once deemed cost prohibitive by many, have an active role in the integration of VERs and in the real-time control of power flows across the power grid. At the residential scale, market forces are driving towards smart energy appliances of nearly every type [52], [54], [162].

In conclusion, the concept of enterprise control provides a working framework upon which to build holistic approaches to control and assessment. Such an approach can facilitate methods that directly address the five holistic dynamic properties discussed: dispatchability, flexibility, forecastability, stability, and resilience. These properties then become the guiding principles upon which the implementation of control technologies can be based. Otherwise, it is possible to introduce solutions that are overlapping in function, over-built and costly. Holistic assessment can help a transition from the existing technology-push scheme to one which is much more requirements driven.

IV. ADEQUACY OF EXISTING ASSESSMENT METHODS

It is in the context of the evolution of the physical power grid described in Section II and the corresponding evolution in the power grid enterprise control described in Section III that the discussion can turn to the adequacy of existing assessment methods. Over the many decades, the fields of electric power engineering and economics have developed a rich and diverse set of assessment techniques to assure reliability and maximize overall economics [5], [74]. Unit commitment, optimal power flow, contingency analysis, state estimation, as well as angular, frequency and voltage stability are but a prominent few. Furthermore, they have been implemented in countless technical standards, codes and regulations [35]–[37]. A full review of these is certainly intractable and assumed as prerequisite. Furthermore, the rationale presented in this paper advocates the enhancement, evolution and combination of these many techniques in holistic frameworks rather than their replacement.

Consequently, in assessing the adequacy of existing methods, the focus is placed on those approaches that facilitate the evolution of the power grid as described in Section II. While the academic literature has produced many works on the role and control of variable energy [89]–[92], demand side [3], [12]–[16], and energy storage resources [95]–[99], many of these works are dedicated to only one of these resource types or only one enterprise control function. In contrast, numerous renewable energy integration studies have emerged in the academic and industrial literature [92], [142], [143], [163] that give a much more holistic understanding of the power grid and its potential evolution in the future. This section proceeds in two parts. Section IV-A discusses the key conclusions and methodological elements from these renewable energy integration studies. Section IV-B then presents some of their limitations that would motivate the need for more holistic assessment methods.

A. Existing Assessment Methods

In order to support the need for holistic enterprise control assessment, a review of existing renewable energy integration studies is conducted from the perspective of the guiding structure found in Figure 1. In order to focus on the most developed methodologies, only integration studies published after 2005 were included. The interested reader is referred to [164] for pre-2005 works. Figure 10 summarizes the analysis of the included works ordered alphabetically by their associated acronym [165]–[194]. This list constitutes a superset of those included in a recent review [92] on the results rather than the methodologies of renewable energy integration studies. Methodologically speaking, Figure 10 addresses the physical layer in terms of the four types of resources shown in Figure 6, the enterprise control in terms of the traditional hierarchical layers of power system operation, and assessment methods in terms of the traditional technical and economic dichotomies shown in Figure 1. The assessment of balancing operations is often viewed through the lens of the quantities of various types of operating reserves. Here, Figure 10 uses the taxonomy of statistical methods developed in Appendix C of [92]. The acronyms used are indicated in the key at the bottom of the figure.

Collectively, the renewable energy integration studies have many similarities [92], [142], [143], [163]. Figure 10 shows that the integration studies generally apply combined unit-commitment and economic dispatch (UCED) models to assess the additional operating costs of renewable energy integration. In contrast, most studies apply statistical methods [92], [142], [143], [163] to assess the required additional operating reserves. The main conclusion of these renewable integration studies is that intermittency and uncertainty will increase reserve requirements in the power system. This will consequently increase the marginal cost of power system operations [92], [195]–[197]. The exact degree of additional operational costs ultimately depends greatly on system properties such as generation mix and fuel cost.

Balancing operations and reserves determination are two of the central objectives of renewable energy integration studies. This work uses the two-group classification of reserves found in [198], [199]. As the first group, event-based reserves respond to contingencies in the system and are also named contingency reserves. Since the outage of any individual wind generation unit has a much smaller impact on the system than the largest thermal plant, wind integration will not increase contingency reserves requirements [198]. Non-event based reserves are normal operational reserves that operate continuously to balance the system in the presence of net load variability and forecast error. They are further classified in Figure 10 by their response times. Load following reserves handle intra-hour variations, ramping reserves allow for ramps between balancing market time steps, and regulation reserves handle minute-to-minute variations of the net load.

The statistical methods used to determine operating reserves are in general variations on the theme found in [200]. The differences between these approaches has been classified by Brouwer et al [92]. In general, the standard deviation of

Acronym	Publication Year	Physical Layer				Cyber-Layer (Control)			Assessment Method for Power System Objectives							
		Dispatchable Generation	Variable Generation	Traditional Load	Demand Side Resources	Unit Commitment	Economic Dispatch	Regulation	Balancing Operation			Line Congestion Management	Voltage Management	Operating Cost	Investment Cost	
									Load Following (Secondary) Reserves	Ramping Reserves	Regulation (Primary) Reserves					
1	CA-MA-WIS [165]	2005	✓	Wind	✓	--	N/A -- Stats Only			--	--	--	--	--	--	--
2	CA-ON-WIS [166]	2006	✓	Wind	✓	--	N/A -- Stats Only			Stat-B-VAR 5min	--	Stat-B-VAR 1min	--	--	--	--
3	EU-AI-REIS [167]	2007	✓	All	✓	--	Gen: 1h	Gen: 1h	Gen: 1h	Stoch-WLF 5min	--	Stat-D2-WLF	--	--	UCED	--
4	EU-IB-WIS [168]	2006	✓	Wind	✓	--	N/A -- Dynamics Only			--	--	--	--	--	--	--
5	EU-DE-WIS [169]	2005	✓	All	✓	--	N/A -- Stats Only			Stat-D2-WLF 15min	--	--	PFA, N-1CA	DVSM	--	Physical: Lines, Control: Regulators
6	EU-DE-REIS [170]	2010	✓	All	✓	Storage & DSM	G&D: 1h	G&D: 1h	--	Utilized	Residual Load Duration Curve	--	PFA	SVSM	UCED	Physical: Lines
7	EU-NL-WIS [171]	2009	✓	Wind	✓	Storage	Gen: 1h	Gen: 1h	Gen: 1s	--	--	--	--	--	UCED	--
8	EU-SE-WIS [172]	2005	✓	All	✓	--	N/A -- Stats Only			Stat-B-WLF 1h	--	Stat-B-WLF 15min	--	--	--	--
9	EU-REIS [173]	2012	✓	All	✓	Storage & DSM	G&D: 1h	G&D: 1h	--	Utilized	Residual Load Duration Curve	--	--	--	UCED	Physical: Generation
10	EU-WIS [174]	2010	✓	All	✓	--	Gen: 1h	Gen: 1h	Gen: 1s	--	--	--	PFA, N-1CA	DVSM	UCED	Physical: Lines
11	EU-TW-WIS [175]	2009	✓	Wind	✓	--	Gen: 1h	Gen: 1h	--	--	--	--	PFA	--	UCED	--
12	EU-UK-WIS [176]	2007	✓	Wind	✓	--	N/A -- Stats Only			Stat-B-WLF 30min	--	--	--	--	--	--
13	EU-WI-WIS [177]	2005	✓	Wind	✓	--	--	Gen: 5min	Gen: 1s	Utilized	--	Utilized	UCED	--	UCED	--
14	US-AV-WIS [178]	2007	✓	Wind	✓	Storage	Gen: 1h	Gen: 1h	--	Stat-B-VAR 10min	--	Stat-B-VAR 10min	--	--	UCED	--
15	US-AZ-SIS [179]	2012	✓	Solar	✓	--	N/A -- Stats Only			Stat-D1-WLF 10min	--	--	--	--	Stat	--
16	US-CA-REIS [180]	2010	✓	All	✓	--	Gen: 1h	Gen: 5min	Gen: 1s	Stoch 5min	Stoch 1min	Stoch 1min	--	--	UCED	--
17	US-E-WIS [181]	2010	✓	Wind	✓	--	Gen: 1h	Gen: 1h	--	Stat-D1-WLF Minutes	--	--	--	--	UCED	--
18	US-ERC-REIS [182]	2008	✓	All	✓	--	Gen: 1h	Gen: 1h	--	--	--	Stat-B/ D1-WLF	--	--	UCED	--
19	US-HA-WIS [183]	2011	✓	All	✓	--	Gen: 1h	Gen: 1h	Gen: 1s	Stat-D1 10min	--	Stat-D1 1s	--	--	UCED	--
20	US-ID-SIS [184]	2014	✓	Solar	✓	--	--	Gen: 1h	--	Stat-B 5min	--	--	--	--	UCED	--
21	US-MN-WIS [185]	2006	✓	Wind	✓	--	Gen: 1h	Gen: 1h	--	Stat-B-VAR Minutes	--	Stat-B-Var	PFA	--	UCED	--
22	US-NE-WIS [186]	2010	✓	Wind	✓	--	Gen: 1h	Gen: 10min	--	Stat-D1 10min	--	Stat-D1 10min	--	--	UCED	--
23	US-NEng-WIS [187]	2010	✓	Wind	✓	--	Gen: 1h	Gen: 1h	--	Stat-B 10min	--	Stat-B 10min	--	--	--	--
24	US-NV-SIS [188]	2011	✓	Solar	✓	--	Gen: 1h	Gen: 10min	Gen: 2-4s	Stat-B-VAR 10min	Stat-VAR-1min	Stat-B-VAR 1min	--	--	UCED	--
25	US-NY-WIS [189]	2005	✓	Wind	✓	--	Gen: 1h	Gen: 1h	--	Stat-B-Var 5min	--	Stat-B-Var	--	DVSM	UCED	--
26	US-P-WIS [190]	2010	✓	Wind	✓	--	Gen: 1h	Gen: 1h	Gen: 10min	Stat-B-VAR 1h	--	Stat-B-VAR 10min	--	--	UCED	--
27	US-PJM-REIS [191]	2013	✓	All	✓	--	Gen: 1h	Gen: 1h	--	Stat-D1-VAR 10min	--	Stat-D1-VAR 10min	Trans. overlay	--	UCED	Physical: Lines
28	US-SPP-WIS [192]	2010	✓	Wind	✓	--	Gen: 1h	Gen: 1h	--	Stat-B-WLF 10min	--	Stat-B-WLF	PFA, N-1CA	SVSM	UCED	--
29	US-W-WSIS [193]	2010	✓	All	✓	--	Gen: 1h	Gen: 5min	Gen: 1min	Stat-D1-VAR	--	--	PFA	--	UCED	--
30	US-W-WSIS2 [194]	2013	✓	All	✓	--	Gen: 1h	Gen: 5min	Gen: 1min	Stat-D1-VAR	--	Stat-D1-WLF	PFA	--	UCED	--

Key: PFA -- Power Flow Analysis, N-1CA -- N-1 Contingency Analysis, DVSM - Dynamic Voltage Stability Model, Static Voltage Stability Model

Fig. 10. An Analysis of Scope and Methods in Renewable Energy Integration Studies

potential imbalances, σ , is calculated using the probability distribution of net load or forecast error. The load following and regulation reserve requirements are then defined to cover appropriate confidence intervals of the distribution based on the experience of power system operators and existing stan-

dards. Normally, load following is taken equal to 2σ [200], [201] to comply with the North American Electric Reliability Corporation (NERC) balancing requirements: NERC defines the minimum score for Control Performance Requirements 2 (CPS2) equal to 90% [140]. This corresponds to 2σ for a

normal distribution. Other integration studies have used a 3σ confidence interval [202], [203] to correspond to the industry standard of 95% [204]. Based on the experience of power system operators, regulation is normally taken to be between 4σ and 6σ [200], [201], [205].

B. Limitations of Existing Assessment Methods

The discussion of the limitations of existing assessment methods is guided by the structure of Figure 1, builds upon the arguments of the previous sections and draws upon the results found in Figure 10. Additionally, and wherever appropriate, the methodological insights and recommendations found in existing renewable energy integration studies are mentioned.

1) *Physical Layer*: In regards to the power grid's physical layer, Figure 10 shows that wind (rather than solar) power has attracted relatively more attention given its greater environmental potential in the geographies committed to renewable energy integration. That said, demand side resources including energy storage and electric vehicles are almost entirely absent methodologically from these studies. Nevertheless, several prominent studies do mention the need to include demand side management directly [170], [174]. Such considerations are particularly important as traditional load and renewable energy penetration grows [92], [142].

2) *Enterprise Control Layers*: In regards to the power system enterprise control, Figure 10 shows that most renewable energy integration studies use simulations based upon an integrated UCED model. Fewer studies add a model of regulation as a separate ancillary service. These three enterprise control layers are conducted primarily to assess the additional operating cost of renewable energy integration and are not integrated with a model of the physical grid to calculate technical variables such as potential power grid imbalances [92], [171], [206]. One often cited concern is that these simulations do not correspond to the existing enterprise control practice. For example, time steps, market structure and physical constraints should correspond to the operating reality [92], [141]–[143], [207]. In the case of market time step size, it has been confirmed both numerically [142], [143], [197] as well as analytically [208]–[210] to affect power grid imbalances and costs. Such a conclusion inextricably ties power system operation and control to their associated policies and regulations. For example, the recent FERC requirement to change the minimum frequency of the balancing market from 1 hour to 15 minutes has an associated impact on power grid technical and economic measures.

The general omission of demand side resources from the physical layer is also recognized in the enterprise control layers as well. The few integration studies that have discussed demand side management; assume an “emergency” management structure where consumers agree to curb their loads at specified times; perhaps in response to a contingency or ramp event [170], [174]. However, such an approach does not consider “economic-control” of demand side resources as it has been implemented in some power system operators [63]. Again, the precise representation of the market structure in simulation matters [92], [141]–[143], [207]. Customers that

respond in real-time to market prices will have drastically different technical and economic effects on the grid than customers that bid as virtual power plants into well-established market structures. Some recent work has demonstrated demand side management integration scenarios that cause grid instability and volatility [60]–[62]. Therefore, it is likely that future integration studies will not just be an instrument for integrating more variable energy resources but also an instrument for designing effective market and control structures through policy and regulation.

3) *Balancing Operation & Reserves Determination*: With respect to balancing operations and reserves determination, the first limitation is the lack of methodological consensus [92], [141]. Such differences if they were applied to the datasets of a single study would show widely diverging results, thus indicating a need for development of the science in renewable energy integration. Some studies assume that standard deviation of power system imbalances is equivalently determined by the net load variability [200], [205], [211] while other assume that it is equivalent to the forecast error [203], [212]–[214]. Intuitively speaking a perfectly forecasted but highly variable net load still requires more non-event reserves than a modestly variable net load. Similarly, a high forecast error will require greater reserves than a low error. Therefore, a true determination of non-event reserves is likely to depend on both variables and not just one [208]–[210]. Moreover, many integration studies are limited to statistical calculations only and their results are not validated by simulation [199], [215]. Those wind power integration studies that do use simulation usually do so for a particular study area [216]. Furthermore, not all studies consider the different timescales of operation. Reference [204] does not consider regulation because the available data has 10 minute resolution. References [211], [215] implement only unit commitment models, according to the assumption that wind integration has the biggest impact on unit commitment.

Figure 10 shows that another concern is the usage and treatment of different power system timescales in the integration studies. Load following and regulation reserves operate at different but overlapping timescales. Net load variability, as a property exists in all timescales, although with changing magnitudes. Forecast error appears in exactly two timescales: 1 hour (day-ahead forecast error) and 5-15 minutes (short term forecast error). Thus, VER intra-hour variability and day-ahead forecast error are relevant to load following reserve requirements. Meanwhile, 5-15 minute variations and short-term forecast error are relevant to regulation reserve requirements. This division of impacts is not carefully addressed in the literature. In [200], the standard deviation σ is measured based upon the total variability of the net load. The loading following and regulation reserve requirements are then calculated on the basis of the *total* variability. Such an approach contradicts that these two control techniques act in different timescales.

Similar timescale concerns apply to studies that use forecast errors. For example, one study [202] calculates both load following and regulation requirements from the standard deviation of the day-ahead forecast error, and does not consider short-term forecast error. In contrast, another study [204] distinguishes between three different timescales of power

system imbalances. The first timescale is regulation which is the difference between the 10 minute average net load and the minute-by-minute net load. The second is load following which is the difference between the hourly average net load and the 10 minute average net load. The final timescale is imbalance, defined as the difference between the hourly forecasted net load and the hourly average net load. In other words, the following three factors are considered: intra-hour variability, minute-by-minute variability and day-ahead forecast error. The timescale distinctions in this study correspond well to the power system operating reserve definitions.

Returning again to the issue of enterprise control, another issue is that in using a statistical approach, the determination of operating reserves rarely considers operating procedures and control techniques [141], [208]–[210]. For example, the heuristic of 2σ for load following and 4σ for regulation is based upon fixed dynamic characteristics of the power system enterprise control and practical experience of the system operators. For example, the recent FERC requirement to change the minimum frequency of the balancing market from 1 hour to 15 minutes would certainly change reserve requirements [142], [143], [197], [208]–[210]. Similarly, the time step of the resource scheduling (day-ahead) market can change. Generally speaking, from a control theory perspective, it is insufficient to characterize the reliability of a system purely on the basis of the magnitude of a disturbance without equally considering the control functions that attenuate this disturbance. More plainly, the reliability of the power grid depends not just on the quantity and timescale of the reserves but also the manual, semi-automatic and automatic control procedures that utilize them.

Another point of focus is the definition of load following and regulation requirements based on NERC requirements and operator experience. The statement that 2σ approximately corresponds to 90% of probability is true when variability/forecast error has a normal probability distribution, which is normally not true [71], [217]–[219]. This assumption can be justified using the central limit theorem [220] in the case of deep wind penetration with significantly wide geographical dispersion. This condition limits the utility of the methodology for the cases of little penetration. Also, the definition of regulation as 5σ or 6σ is based on the experience of operators, which is not necessarily applicable to the new conditions, when the whole dynamics of the power system change [208]–[210].

In addition to these methodological limitations, it is unlikely that a statistical approach to reserves determination is sufficient to describe the adequacy of the enterprise control balancing operations. For example, power system flexibility has thus far been treated implicitly in UCED models [142], [143]. Further works [221]–[223] are seeking to develop specific flexibility measures as mentioned in Section III-B. Similarly, various European grid codes are requiring wind power plants to contribute regulation reserves in primary frequency control [35]–[37]. Although such a requirement would immediately reduce wind variability, rarely is it considered in integration studies. As the methodologies in renewable energy integration studies continue to develop it is more likely there will be a shift towards simulation-based [224]–[230] and analytical

[208]–[210] techniques.

4) *Line Congestion & Voltage Management*: While balancing operations have been the focus of renewable energy integration studies, Figure 10 shows that some have also included line congestion and voltage management within their scope. In regards to line congestion management, power flow and N-1 contingency analyses are conducted as a post-process to the UCED simulation results. Holttinen et al. suggest instead that these should analyses be integrated [142], [143]. Furthermore, Muzhikyan et al. have demonstrated that power flow analysis as a physical model of the power grid serves to recalibrate the UCED simulation [224]–[229]. More fundamentally, however, line congestion and the stability of balancing operations are ultimately coupled [86]–[88] and should be integrated in simulation [141]. Aspects of such an approach were begun in the DENA 2010 study [170]. With respect to voltage management, the applicable integration studies are split between static and dynamic models. Again, Holttinen et al. agree with the DENA 2010 study to use dynamic models over key time periods of interest [142], [143]. They also advocate considering the effects of different wind turbine technologies, droop and regulator settings etc. Such a recommendation is insightful. If generalized, it could ultimately provide a working framework for the technical assessment of various control technology integrations as mentioned in Section III-C. These may include variable energy and demand side resources and their respective controllers. This also suggests that renewable energy integration studies are likely to become instruments that influence grid code standards in addition to market and control structure as previously discussed.

5) *Economic Assessment*: In regards to the economic assessment in renewable energy integration studies, Figure 10 shows that most are focused on operational costs through UCED simulation models. Comparatively few address the additional investment costs of physical infrastructure be it in the form of generation or transmission expansion. Interestingly, the DENA 2010 study [170] includes the investment cost of voltage regulators to abate line congestion. Similarly, Mohseni et al. [36] advocate that new grid codes consider the associated investments costs of the requirements that they impose. In contrast, Diaz-Gonzalez et al. [37] describe grid code requirements on the frequency response of wind turbines with no mention of the costs incurred by providing this ancillary service while running in an sub-optimal state. These are telling precedents. They suggest the need to assess the investment costs of various control technologies against the technical improvements that they provide. If such an approach were generalized, it could form the basis for accurate assessments of the long term investment costs of future “smart” grids.

In conclusion, renewable energy integration studies as a collective body of literature give a much more holistic understanding of the power grid and its potential evolution in the future. While these studies continue to evolve, they have yet to incorporate the real potential of demand side resources; the fourth quadrant in Figure 6. Furthermore, in regards to balancing operation, they use statistical methods for which there is a lack of consensus and which are based upon questionable assumptions. It is likely that the assessment

of reserves will ultimately shift to simulation-based and analytical methods. UCED simulations form an integral piece of most integration studies and are likely to remain so. However, several authors have already advocated for the need to maintain the coherence between market operating procedures and the simulations. Such a coherence has been suggested equally well in the enterprise control as in the physical layer where line congestion, dynamic stability and voltage management requirements become coupled. Finally, as these simulations gain greater fidelity – representing more of energy and control technology integration decisions, it is likely that they will come to include the associated investment costs.

V. A FRAMEWORK FOR HOLISTIC POWER GRID ENTERPRISE CONTROL ASSESSMENT

The literature gap identified in the previous section can be addressed by a framework for holistic power grid enterprise control assessment. Such an approach is in agreement with several recommendations in the literature for integrated approaches [141]–[143], [171]. Furthermore, one work advocates the role of custom-built simulators to assess the future electricity grid [231].

Gathering the discussions from the previous sections, such a framework has the following requirements:

- allows for an evolving mixture of generation and demand as dispatchable energy resources
- allows for an evolving mixture of generation and demand as variable energy resources
- allows for the simultaneous study of transmission and distribution systems
- allows for the time domain simulation of the convolution of relevant grid enterprise control functions
- allows for the time domain simulation of power grid topology reconfiguration in the operations time scale.
- specifically address the holistic dynamic properties of dispatchability, flexibility, forecastability, stability, and resilience
- represents potential changes in enterprise grid control functions and technologies as impacts on these dynamic properties.
- accounts for the consequent changes in operating cost and the required investment costs

The first five of these requirements are basically associated with the nature of the power grid itself as it evolves. In the meantime, the next two are associated with the behavior of the power grid in the operations time scale. Finally, the last requirement contextualizes the simulation with cost accounting.

To that effect, Figure 11 represents a recently developed conceptual design of a reconfigurable power system simulator that implements enterprise control [224]–[230]. The simulator includes the physical electrical grid layer and incorporates primary, secondary and tertiary control functions. These layers may be modified as necessary to assess the impact of a given control function and technology on the time domain simulation.

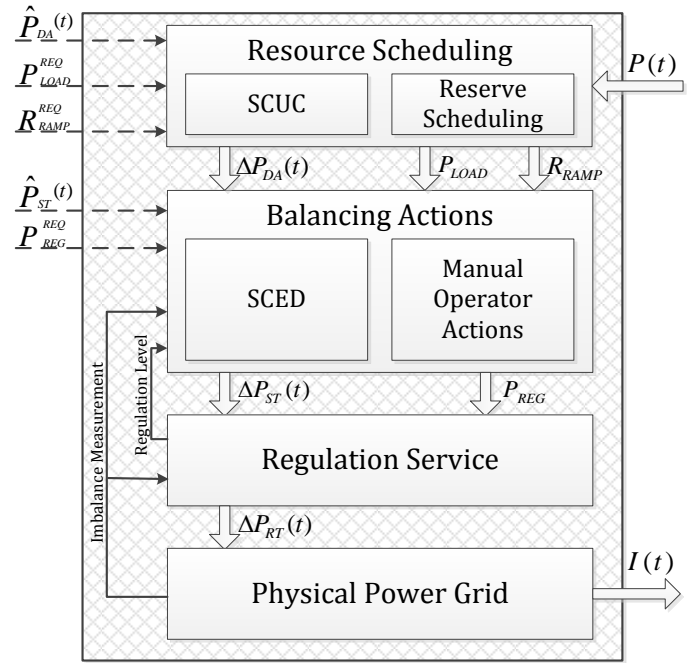


Fig. 11. Conceptual Design of an Enterprise Control Power Grid Simulator

Such an approach has several advantages. First, the net load may be viewed as a system disturbance which is systematically rejected by forecasting and relevant enterprise control functions to give a highly attenuated system imbalance time domain signal. An implementation of this conceptual design has been completed to systematically study the evolution of power system imbalances in relation to enterprise control functions typically found in American transmission systems [224]–[230]. Second, it can address the recommendations in the literature [207] to assess the impact of variable amounts of variable generation on ancillary services. Such an approach can help build the previously identified lack of a systematic and case-independent knowledge base towards renewable energy integration [143] that specifically considers enterprise control functions in markets [232] and demand side resources [230], [233]–[237].

VI. CONCLUSION

This paper has argued the need for holistic enterprise control assessment methods for the future electricity grid. As driven by decarbonization, reliability, transportation electrification, consumer participation and deregulation, this future grid will undergo technical, economic and regulatory changes to bring about the incorporation of renewable energy and incentivized demand side management and control. As a result, the power grid will experience fundamental changes in its system structure and behavior that will consequently require enhanced and integrated control, automation, and IT-driven management functions in what is called enterprise control. While these requirements will open a plethora of opportunities for new control technologies, many of which are largely overlapping in function. Their overall contribution to holistic dynamic properties such as dispatchability, flexibility, forecast ability,

and voltage stability is less than clear. Piece-meal integration and a lack of coordinated assessment could bring about costly-overbuilt solutions or even worse unintended technical consequences. It is upon this three-part foundation that the paper turned to discuss the adequacy of existing assessment methods. The focus of this discussion was the existing state of the renewable energy integration study literature as the most holistic set of assessment methods available. While these studies continue to evolve, they have yet to fully incorporate demand side management and more robust simulation-based approaches. The paper concludes with a framework for holistic power grid enterprise control assessment built upon the conceptual design of the corresponding simulator. Initial demonstrations of this framework are already reported and more holistic power system studies are envisioned.

ACKNOWLEDGMENT

The authors would like to acknowledge and thank their colleagues & co-authors on the MIT Future of the Electricity Grid Study [45] and the IEEE CSS Smart Grid Vision [6] for numerous constructive conversations leading to the completion of this work.

REFERENCES

- [1] A. von Meier, *Electric power systems : a conceptual introduction*. Hoboken, N.J.: IEEE Press : Wiley-Interscience, 2006. [Online]. Available: <http://ieeexplore.ieee.org/xpl/bkabstractplus.jsp?bkn=5238205>
- [2] P. Schavemaker, L. Van der Sluis, and Books24x7 Inc., *Electrical power system essentials*. Chichester, England ; Hoboken, NJ: Wiley, 2008. [Online]. Available: <http://www.loc.gov/catdir/enhancements/fy0810/2008007359-d.htmlhttp://www.loc.gov/catdir/enhancements/fy0810/2008007359-t.html>
- [3] C. W. Gellings, "The concept of demand-side management for electric utilities," *Proceedings of the IEEE*, vol. 73, no. 10, pp. 1468–1470, 1985.
- [4] A. J. Wood and B. F. Wollenberg, *Power generation, operation, and control*, 3rd ed. Hoboken, NJ, USA: John Wiley & Sons, 2014.
- [5] A. Gomez Exposito, A. J. Conejo, C. Canizares, A. Gómez-Expósito, and C. Cañizares, *Electric energy systems: analysis and operation*. Boca Raton, Fla: CRC, 2008, vol. The electr, no. Recommended.
- [6] A. M. Annaswamy, M. Amin, C. L. Demarco, T. Samad, J. Aho, G. Arnold, A. Buckspan, A. Cadena, D. Callaway, E. Camacho, M. Caramanis, A. Chakraborty, A. Chakraborty, J. Chow, M. Dahleh, A. D. Dominguez-Garcia, D. Dotta, A. M. Farid, P. Flikkema, D. Gayme, S. Genc, M. G. i. Fisa, I. Hiskens, P. Houpt, G. Hug, P. Khargonekar, H. Khurana, A. Kiani, S. Low, J. McDonald, E. Mojica-Nava, A. L. Motto, L. Pao, A. Parisio, A. Pinder, M. Polis, M. Roozbehani, Z. Qu, N. Quijano, and J. Stoustrup, *IEEE Vision for Smart Grid Controls: 2030 and Beyond*, A. M. Annaswamy, M. Amin, C. L. Demarco, and T. Samad, Eds. New York NY: IEEE Standards Association, 2013. [Online]. Available: <http://www.techstreet.com/ieee/products/1859784>
- [7] N. H. Stern and Great Britain. Treasury., *The economics of climate change : the Stern review*. Cambridge, UK ; New York: Cambridge University Press, 2007.
- [8] EuropeanCommission, "A Roadmap for Moving to a Competitive Low Carbon Economy in 2050," European Commission, Brussels, Belgium, Tech. Rep., 2011. [Online]. Available: http://eur-lex.europa.eu/resource.html?uri=cellar:5db26ecc-ba4e-4de2-ae08-dba649109d18.0002.03/DOC_1&format=PDF
- [9] European Parliament and of the Council, "Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC," *Official Journal of the European Union*, vol. L140/16, pp. 16–62, 2009.
- [10] IEA, "World Energy Outlook," International Energy Agency, Paris, France, Tech. Rep., 2013.
- [11] USEIA, "International Energy Outlook 2013," U.S. Energy Information Administration, Washington, D.C., Tech. Rep., 2013. [Online]. Available: [http://www.eia.gov/forecasts/ieo/pdf/0484\(2013\).pdf](http://www.eia.gov/forecasts/ieo/pdf/0484(2013).pdf)
- [12] G. Strbac, "Demand side management: Benefits and challenges," *Energy Policy*, vol. 36, no. 12, pp. 4419–4426, 2008. [Online]. Available: <http://dx.doi.org/10.1016/j.enpol.2008.09.030>
- [13] M. H. Albadi and E. F. El-Saadany, "A summary of demand response in electricity markets," *Electric Power Systems Research*, vol. 78, no. 11, pp. 1989–1996, 2008. [Online]. Available: <http://dx.doi.org/10.1016/j.epr.2008.04.002>
- [14] S. C. Breukers, E. Heiskanen, B. Brohmann, R. M. Mourik, and C. F. J. Feenstra, "Connecting research to practice to improve energy demand-side management (DSM)," *Energy*, vol. 36, no. 4, pp. 2176–2185, 2011. [Online]. Available: <http://www.sciencedirect.com/science/article/B6V2S-5143BB2-1/2/3fb607ec5b39f6ce6f7c143028ec420>
- [15] J. Aghaei and M.-i. Alizadeh, "Demand response in smart electricity grids equipped with renewable energy sources : A review," *Renewable and Sustainable Energy Reviews*, vol. 18, pp. 64–72, 2013.
- [16] P. Siano, "Demand response and smart grids—A survey," *Renewable and Sustainable Energy Reviews*, vol. 30, pp. 461–478, Feb. 2014. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1364032113007211>
- [17] G. Pasaoglu, M. Honselaar, and C. Thiel, "Potential vehicle fleet CO2 reductions and cost implications for various vehicle technology deployment scenarios in Europe," *Energy Policy*, vol. 40, pp. 404–421, 2012. [Online]. Available: <http://dx.doi.org/10.1016/j.enpol.2011.10.025>
- [18] T. Litman, "Comprehensive Evaluation of Transport Energy Conservation and Emission Reduction Policies," *Transportation Research Part: Policy and Practice*, vol. 47, pp. 1–23, 2013.
- [19] D. Anair and A. Mahmassani, "State of Charge: Electric Vehicles' Global Warming Emissions and Fuel-Cost Savings across the United States," Union of Concerned Scientists: Citizens and Scientists for Environmental Solutions, Cambridge, MA, USA, Tech. Rep. April, 2012.
- [20] M. D. Galus, R. a. Waraich, F. Noembrini, K. Steurs, G. Georges, K. Boulouchos, K. W. Axhausen, and G. Andersson, "Integrating Power Systems, Transport Systems and Vehicle Technology for Electric Mobility Impact Assessment and Efficient Control," *IEEE Transactions on Smart Grid*, vol. 3, no. 2, pp. 934–949, Jun. 2012. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6204241>
- [21] R. Al Junaibi, "Technical Feasibility Assessment of Electric Vehicles in Abu Dhabi," Master's Thesis, Masdar Institute of Science and Technology, 2013. [Online]. Available: <http://amfarid.scripts.mit.edu/page19/styled-4/index.html>
- [22] R. Al Junaibi, A. Viswanath, and A. M. Farid, "Technical Feasibility Assessment of Electric Vehicles : An Abu Dhabi Example," in *2nd IEEE International Conference on Connected Vehicles and Expo*, Las Vegas, NV, USA, 2013, pp. 1–8. [Online]. Available: <http://dx.doi.org/10.1109/ICCVE.2013.6799828>
- [23] W. Su, H. Rahimi-eichi, W. Zeng, and M.-y. Chow, "A Survey on the Electrification of Transportation in a Smart Grid Environment," *IEEE Transactions on Industrial Informatics*, vol. 8, no. 1, pp. 1–10, 2012.
- [24] F. Salah, J. P. Ilg, C. M. Flath, H. Basse, and C. van Dinther, "Impact of electric vehicles on distribution substations: A swiss case study," *Applied Energy*, vol. 137, no. 0, pp. 88 – 96, 2015. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0306261914010393>
- [25] H.-p. Chao and H. G. Huntington, *Designing competitive electricity markets*. Boston, Mass: Kluwer Academic, 1998. [Online]. Available: <http://www.loc.gov/catdir/enhancements/fy0819/98036769-d.htmlhttp://www.loc.gov/catdir/enhancements/fy0819/98036769-t.html>
- [26] M. D. Ilic, F. D. Galiana, and L. H. Fink, *Power systems restructuring : engineering and economics*. Boston: Kluwer Academic Publishers, 1998. [Online]. Available: <http://www.loc.gov/catdir/enhancements/fy0821/98006642-d.htmlhttp://www.loc.gov/catdir/enhancements/fy0821/98006642-t.html>
- [27] W. Hogan, "Electricity Market Restructuring: Reforms of Reforms," *Journal of Regulatory Economics*, vol. 21, no. 1, pp. 103–132, 2002. [Online]. Available: <http://dx.doi.org/10.1023/A:1013682825693>
- [28] S. Stoft, *Power System Economics: Designing Markets for Electricity*, 1st ed. Wiley-IEEE Press, 2002.
- [29] M. Shahidepour, H. Yamin, and Z. Y. Li, *Market Operations in Electric Power Systems*. New York, New York, USA: New York: Wiley, 2002.
- [30] D. S. Kirschen and G. Strbac, *Fundamentals of Power System Economics*. Chichester, West Sussex, England ; Hoboken,

- NJ: John Wiley & Sons Ltd, 2004. [Online]. Available: <http://www.loc.gov/catdir/description/wiley041/2004004942.html><http://www.loc.gov/catdir/toc/wiley041/2004004942.html>
- [31] M. Shahidehpour and Z. Li, *Electricity market Economics*. New York: John Wiley and Sons, 2005.
- [32] A. Garcia, L. Mili, and J. Momoh, "Modeling Electricity Markets: A Brief Introduction," in *Economic Market Design and Planning for Electric Power Systems*. John Wiley & Sons, Inc., 2009, pp. 21–44. [Online]. Available: <http://dx.doi.org/10.1002/9780470529164.ch2>
- [33] W. W. Hogan, "Electricity Whole-sale Market Design in a Low-Carbon Future," in *Harnessing renewable energy in electric power systems : theory, practice, policy*. Washington, DC: RFF Press, 2010, pp. 113–136.
- [34] —, "Multiple Market-Clearing Prices, Electricity Market Design and Price Manipulation," *The Electricity Journal*, vol. 25, no. 4, pp. 18–32, May 2012. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S1040619012000917>
- [35] Anonymous, "The Grid Code," National Grid Electricity Transmission plc, Warwick, UK, Tech. Rep., 2012.
- [36] M. Mohseni and S. M. Islam, "Review of international grid codes for wind power integration: Diversity, technology and a case for global standard," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 6, pp. 3876–3890, Aug. 2012. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1364032112002225>
- [37] F. Diaz-Gonzalez, M. Hau, A. Sumper, and O. Gomis-Bellmunt, "Participation of wind power plants in system frequency control : Review of grid code requirements and control methods," *Renewable and Sustainable Energy Reviews*, vol. 34, pp. 551–564, 2014.
- [38] C. Gellings, "Estimating the Costs and Benefits of the Smart Grid," EPRI, Palo Alto, CA, USA, Tech. Rep., 2011.
- [39] B. Easton, K. House, and J. Byars, "Smart Grid : a race worth winning ? A report on the economic benefits of smart grid," Ernst & Young, London, UK, Tech. Rep. April, 2012.
- [40] A. D. Ellerman and B. K. Buchner, "The European Union Emissions Trading Scheme: Origins, Allocation, and Early Results," *Review of Environmental Economics and Policy*, vol. 1, no. 1, pp. 66–87, 2007.
- [41] REN21, "Renewables 2014 Global Status Report," REN 21 Renewable Energy Policy Network for the 21st Century, Paris, France, Tech. Rep., 2014.
- [42] J. J. Dooley, "U.S. Federal Investments in Energy R&D: 1961-2008," Pacific Northwest National Laboratory & United States Department of Energy, Oak Ridge, TN, Tech. Rep. October, 2008.
- [43] California-PUC, "California Renewables Portfolio Standard (RPS)," San Francisco, CA, 2002. [Online]. Available: <http://www.cpuc.ca.gov/PUC/energy/Renewables/index.htm>
- [44] North Carolina Solar Center, "Database for State Incentives for Renewables and Energy Efficiency," Raleigh, North Carolina, 2014. [Online]. Available: <http://www.dsireusa.org/>
- [45] J. G. Kassakian, R. Schmalensee, G. Desgroseilliers, T. D. Heidel, K. Afridi, A. M. Farid, J. M. Grochow, W. W. Hogan, H. D. Jacoby, J. L. Kirtley, H. G. Michaels, I. Perez-Arriaga, D. J. Perreault, N. L. Rose, G. L. Wilson, N. Abudalrah, M. Chen, P. E. Donohoo, S. J. Gunter, P. J. Kwok, V. A. Sakhrani, J. Wang, A. Whitaker, X. L. Yap, R. Y. Zhang, and M. I. of Technology, *The Future of the Electric Grid: An Interdisciplinary MIT Study*. Cambridge, MA: MIT Press, 2011. [Online]. Available: http://web.mit.edu/mitei/research/studies/documents/electric-grid-2011/Electric_Grid_Full_Report.pdf
- [46] C. C. Chan, "The State of the Art of Electric, Hybrid, and Fuel Cell Vehicles," *Proceedings of the IEEE*, vol. 95, no. 4, pp. 704–718, 2007.
- [47] K. Yabe, Y. Shinoda, T. Seki, H. Tanaka, and A. Akisawa, "Market penetration speed and effects on CO 2 reduction of electric vehicles and plug-in hybrid electric vehicles in Japan," *Energy Policy*, vol. 45, pp. 529–540, 2012. [Online]. Available: <http://dx.doi.org/10.1016/j.enpol.2012.02.068>
- [48] M. Weiss, M. K. Patel, M. Junginger, A. Perujo, P. Bonnel, and G. V. Grootveld, "On the electrification of road transport - Learning rates and price forecasts for hybrid-electric and battery-electric vehicles," *Energy Policy*, vol. 48, pp. 374–393, 2012. [Online]. Available: <http://dx.doi.org/10.1016/j.enpol.2012.05.038>
- [49] Y. Ma, T. Houghton, A. Cruden, and D. Infield, "Modeling the Benefits of Vehicle-to-Grid Technology to a Power System," *Power Systems, IEEE Transactions on*, vol. 27, no. 2, pp. 1012–1020, 2012.
- [50] Y. Ota, H. Taniguchi, T. Nakajima, K. M. Liyanage, J. Baba, and A. Yokoyama, "Autonomous Distributed V2G (Vehicle-to-Grid) Satisfying Scheduled Charging," *Smart Grid, IEEE Transactions on*, vol. 3, no. 1, pp. 559–564, 2012.
- [51] E. Sortomme and M. A. El-Sharkawi, "Optimal Scheduling of Vehicle-to-Grid Energy and Ancillary Services," *Smart Grid, IEEE Transactions on*, vol. 3, no. 1, pp. 351–359, 2012.
- [52] V. C. Gungor and F. C. Lambert, "A survey on communication networks for electric system automation," *Computer Networks*, vol. 50, no. 7, pp. 877–897, May 2006. [Online]. Available: <http://dx.doi.org/10.1016/j.comnet.2006.01.005>
- [53] S. S. S. R. Depuru, L. Wang, and V. Devabhaktuni, "Smart meters for power grid: Challenges, issues, advantages and status," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 6, pp. 2736–2742, Aug. 2011. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1364032111000876>
- [54] Y. Yan, Y. Qian, H. Sharif, and D. Tipper, "A survey on smart grid communication infrastructures: Motivations, requirements and challenges," *IEEE Communications Surveys and Tutorials*, vol. 15, no. 1, pp. 5–20, 2013. [Online]. Available: <http://dx.doi.org/10.1109/SURV.2012.021312.00034>
- [55] K. Reddy, M. Kumar, T. Mallick, H. Sharon, and S. Lokeswaran, "A review of Integration, Control, Communication and Metering (ICCM) of renewable energy based smart grid," *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 180–192, Oct. 2014. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1364032114003748>
- [56] K. Iniewski and T. Mozel, *Power Line Communication Technology for Smart Grids, Smart Homes, and Smart Cars*. CMOS Emerging Technologies, 2012.
- [57] V. C. Gungor and F. C. Lambert, "A survey on communication networks for electric system automation," *Computer Networks*, vol. 50, no. 7, pp. 877–897, May 2006. [Online]. Available: <http://dx.doi.org/10.1016/j.comnet.2006.01.005>
- [58] A. Kailas, V. Cecchi, and A. Mukherjee, "A Survey of Communications and Networking Technologies for Energy Management in Buildings and Home Automation," *Journal of Computer Networks and Communications*, p. 932181 (12 pp.), 2012. [Online]. Available: <http://dx.doi.org/10.1155/2012/932181>
- [59] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. P. Hancke, "Smart Grid Technologies: Communication Technologies and Standards," *Industrial Informatics, IEEE Transactions on*, vol. 7, no. 4, pp. 529–539, 2011.
- [60] M. Roozbehani, M. Dahleh, and S. Mitter, "On the Stability of Wholesale Electricity Markets under Real-Time Pricing," in *49th IEEE Conference on Decision and Control (CDC2010)*, Atlanta, Georgia, USA, 2010, pp. 1911–1918.
- [61] —, "Dynamic Pricing and Stabilization of Supply and Demand in Modern Electric Power Grids," in *2010 First IEEE International Conference on Smart Grid Communications*, Gaithersburg, Maryland, USA, 2010, pp. 543–548.
- [62] M. Muratori, B.-A. Schuelke-Leech, and G. Rizzoni, "Role of residential demand response in modern electricity markets," *Renewable and Sustainable Energy Reviews*, vol. 33, pp. 546–553, May 2014. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1364032114001488>
- [63] PJM-ISO, "Demand Side Response," PJM-ISO, Norristown, PA, Tech. Rep., 2011.
- [64] A. M. Farid and A. Muzhikyan, "The Need for Holistic Assessment Methods for the Future Electricity Grid," in *GCC CIGRE Power 2013*, Abu Dhabi, UAE, 2013, pp. 1–12. [Online]. Available: <http://amfarid.scripts.mit.edu/resources/SPG-C08.pdf>
- [65] Bonneville Power Administration, "Wind Generation & Total Load in The BPA Balancing Authority." [Online]. Available: <http://transmission.bpa.gov/business/operations/wind/>
- [66] F. Milano, *Power system modelling and scripting*, 1st ed. New York: Springer, 2010. [Online]. Available: <http://www.uclm.es/area/gsee/web/Federico/psat.htm>
- [67] J. Apt, "The spectrum of power from wind turbines," *Journal of Power Sources*, vol. 169, no. 2, pp. 369–374, Jun. 2007. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0378775307005381>
- [68] A. E. Curtright and J. Apt, "The character of power output from utility-scale photovoltaic systems," *Progress in Photovoltaics: Research and Applications*, vol. 16, no. 3, pp. 241–247, May 2008. [Online]. Available: <http://doi.wiley.com/10.1002/ppp.786>
- [69] S. C. Chan, K. M. Tsui, H. C. Wu, Y. Hou, Y.-C. Wu, and F. F. Wu, "Load/Price Forecasting and Managing Demand Response for Smart Grids: Methodologies and Challenges," *Signal Processing Magazine, IEEE*, vol. 29, no. 5, pp. 68–85, 2012.
- [70] L. R. Christensen and W. H. Greene, "Economies of Scale in U.S. Electric Power Generation," *Journal of Political Economy*, vol. 84, no. 4, pp. 655–676, 1976.

- [71] G. Giebel, R. Brownsword, G. Kariniotakis, M. Denhard, and C. Draxl, *The State-Of-The-Art in Short-Term Prediction of Wind Power: A Literature Overview*, 2nd ed. Roskilde, Denmark: ANEMOS, 2011.
- [72] C. Monteiro, R. Bessa, V. Miranda, A. Botterud, J. Wang, and G. Conzelmann, "Wind Power Forecasting: State-of-the-Art 2009 Decision and Information Sciences Division," *Argonne National Laboratory*, no. November 6, pp. 1–216, 2009. [Online]. Available: http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=968212
- [73] S. Al-Yahyai, Y. Charabi, and A. Gastli, "Review of the use of Numerical Weather Prediction (NWP) Models for wind energy assessment," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9, pp. 3192–3198, Dec. 2010. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1364032110001814>
- [74] L. L. Grigsby, "The electric power engineering handbook," *The electrical engineering handbook series*, 2001. [Online]. Available: <http://www.loc.gov/catdir/enhancements/fy0646/00030425-d.html>
- [75] P. Basak, S. Chowdhury, S. Halder nee Dey, and S. Chowdhury, "A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 8, pp. 5545–5556, Oct. 2012. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1364032112003772>
- [76] S. Ruiz-Romero, A. Colmenar-Santos, F. Mur-Perez, and A. Lopez-Rey, "Integration of distributed generation in the power distribution network: The need for smart grid control systems, communication and equipment for a smart city — Use cases," *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 223–234, Oct. 2014. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S136403211400416X>
- [77] S. Mirsaedi, D. Mat, M. Wazir, and M. Ha, "Progress and problems in micro-grid protection schemes," *Renewable and Sustainable Energy Reviews*, vol. 37, pp. 834–839, 2014.
- [78] S. a. Gopalan, V. Sreeram, and H. H. Iu, "A review of coordination strategies and protection schemes for microgrids," *Renewable and Sustainable Energy Reviews*, vol. 32, pp. 222–228, Apr. 2014. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1364032114000483>
- [79] O. Palizban, K. Kauhaniemi, and J. M. Guerrero, "Microgrids in active network management – part II : System operation , power quality and protection," *Renewable and Sustainable Energy Reviews*, vol. 36, pp. 440–451, 2014. [Online]. Available: <http://dx.doi.org/10.1016/j.rser.2014.04.048>
- [80] R. H. Lasseter, "Smart Distribution: Coupled Microgrids," *Proceedings of the IEEE*, vol. 99, no. 6, pp. 1074–1082, Jun. 2011. [Online]. Available: <http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=5768104&contentType=Journals+&Magazines&queryText=microgrids+lasseter>
- [81] N. Lidula and A. Rajapakse, "Microgrids research: A review of experimental microgrids and test systems," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 1, pp. 186–202, Jan. 2011. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S136403211000328X>
- [82] T. S. Ustun, C. Ozansoy, and A. Zayegh, "Recent developments in microgrids and example cases around the world — A review," *Renewable and Sustainable Energy Reviews*, vol. 15, pp. 4030–4041, 2011.
- [83] N. Hatziaargyriou, *Microgrids: Architectures and Control*. West Sussex, England: Wiley IEEE Press, 2014.
- [84] A. Vaccaro, V. Loia, G. Formato, P. Wall, and V. Terzija, "A self-organizing architecture for decentralized smart microgrids synchronization, control, and monitoring," *Industrial Informatics, IEEE Transactions on*, vol. 11, no. 1, pp. 289–298, Feb 2015.
- [85] M. D. Ilic and J. Zaborszky, *Dynamics and control of large electric power systems*. New York: Wiley, 2000. [Online]. Available: <http://www.loc.gov/catdir/description/wiley031/99029004.html>
<http://www.loc.gov/catdir/toc/onix01/99029004.html>
- [86] P. Kundur, *Power system stability and control*. McGraw-Hill, 1994.
- [87] J. Machowski, J. W. Bialek, and J. R. Bumby, "Power system dynamics : stability and control," pp. xxvii, 629 p., 2008. [Online]. Available: <http://www.loc.gov/catdir/toc/ecip0824/2008032220.html>
- [88] M. Eremia and M. Shahidehpour, *Handbook of electrical power system dynamics : modeling, stability, and control*, M. Eremia and M. Shahidehpour, Eds. Hoboken, N.J.: IEEE Press – John Wiley & Sons, 2013.
- [89] M. H. Albadi and E. F. El-Saadany, "Overview of wind power intermittency impacts on power systems," *Electric Power Systems Research*, vol. 80, no. 6, pp. 627–632, Jun. 2010. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0378779609002764>
- [90] J. Kabouris and F. D. Kanellos, "Impacts of Large-Scale Wind Penetration on Designing and Operation of Electric Power Systems," *Sustainable Energy, IEEE Transactions on*, vol. 1, no. 2, pp. 107–114, 2010.
- [91] G. M. Shafiqullah, A. M. T. Oo, A. B. M. S. Ali, and P. Wolfs, "Potential challenges of integrating large-scale wind energy into the power grid – A review," *Renewable and Sustainable Energy Reviews*, vol. 20, pp. 306–321, 2013.
- [92] A. S. Brouwer, M. van den Broek, A. Seebregts, and A. Faaij, "Impacts of large-scale Intermittent Renewable Energy Sources on electricity systems , and how these can be modeled," *Renewable and Sustainable Energy Reviews*, vol. 33, pp. 443–466, 2014.
- [93] Federal Energy Regulatory Commission, "Order No. 764," FERC, Tech. Rep., 2012.
- [94] M. Wolter, "Reducing the Curtailment Amount of Renewable Energy Using Efficiency-Based Allocation," in *Mathworks Energy and Utilities Virtual Conference*, 2012, pp. 1–2.
- [95] W. F. Pickard, A. Q. Shen, and N. J. Hansing, "Parking the power: strategies and physical limitations for bulk energy storage in supply-demand matching on a grid whose input power is provided by intermittent sources," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 1934–1945, Oct. 2009. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1364032109000562>
<http://dx.doi.org/10.1016/j.rser.2009.03.002>
- [96] M. Beaudin, H. Zareipour, A. Schellenbergglabe, and W. Rosehart, "Energy storage for mitigating the variability of renewable electricity sources: An updated review," *Energy for Sustainable Development*, vol. 14, no. 4, pp. 302–314, Dec. 2010. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0973082610000566>
- [97] F. Diaz-Gonzalez, A. Sumper, O. Gomis-Bellmunt, and R. Villafila-Robles, "A review of energy storage technologies for wind power applications," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 4, pp. 2154–2171, 2012. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S1364032112000305>
- [98] N. S. Hasan, M. Yusri, S. Majid, and H. A. Rahman, "Review of storage schemes for wind energy systems," *Renewable and Sustainable Energy Reviews*, vol. 21, pp. 237–247, 2013.
- [99] M. Y. Suberu, M. W. Mustafa, and N. Bashir, "Energy storage systems for renewable energy power sector integration and mitigation of intermittency," *Renewable and Sustainable Energy Reviews*, vol. 35, pp. 499–514, 2014.
- [100] P. Riederer, "Buildign Simulation: MATLAB/SIMULINK for building and HVAC simulation - State of the Art," in *Ninth International IBPSA Conference*, Montréal, Canada, 2005, pp. 1019–1026.
- [101] S. Wang and Z. Ma, "Supervisory and Optimal Control of Building HVAC Systems: A Review," *HVAC&R Research*, vol. 14, no. 1, pp. 3–32, 2007. [Online]. Available: <http://www.tandfonline.com/doi/abs/10.1080/10789669.2008.10390991>
- [102] S. Wang, *Intelligent buildings and building automation*. London ; New York: Spon Press, 2010.
- [103] P. H. Shaikh, N. B. M. Nor, P. Nallagownden, I. Elamvazuthi, and T. Ibrahim, "A review on optimized control systems for building energy and comfort management of smart sustainable buildings," *Renewable and Sustainable Energy Reviews*, vol. 34, pp. 409–429, Jun. 2014. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1364032114001889>
- [104] X. Li and J. Wen, "Review of building energy modeling for control and operation," *Renewable and Sustainable Energy Reviews*, vol. 37, pp. 517–537, Sep. 2014. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1364032114003815>
- [105] A. ParandehGheibi, M. Roozbehani, M. A. Dahleh, and A. Ozdaglar, "The value of storage in securing reliability and mitigating risk in energy systems," *Energy Systems*, vol. 6, no. 1, pp. 129–152, 2015.
- [106] L. Xie, P. M. S. Carvalho, L. Ferreira, J. Liu, B. H. Krogh, N. Popli, and M. D. Ilic, "Wind Integration in Power Systems: Operational Challenges and Possible Solutions," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 214–232, 2011.
- [107] M. S. Branicky, "Multiple Lyapunov functions and other analysis tools for switched and hybrid systems," *IEEE Transactions on Automatic Control*, vol. 43, no. 4, pp. 475–482, 1998. [Online]. Available: <http://dx.doi.org/10.1109/9.664150>
- [108] J. Lunze and F. Lamnabhi-Lagarrigue, *Handbook of hybrid systems control : theory, tools, applications*. Cambridge, UK ; New York: Cambridge University Press, 2009.

- [109] D. Wei and K. Ji, "Resilient industrial control system (RICS): Concepts, formulation, metrics, and insights," in *3rd International Symposium on Resilient Control Systems, ISRCS 2010*, Idaho Falls, USA, 2010, pp. 15–22.
- [110] C. Rieger and Q. Zhu, "A hierarchical multi-agent dynamical system architecture for resilient control systems," in *2013 6th International Symposium on Resilient Control Systems (ISRCS)*. Ieee, Aug. 2013, pp. 6–12. [Online]. Available: <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6623742>
- [111] C. G. Rieger, K. L. Moore, and T. L. Baldwin, "Resilient Control Systems: A multi-agent dynamic systems perspective," in *2013 IEEE International Conference on Electro/Information Technology (EIT)*, 2013, pp. 1–16.
- [112] A. M. Farid, "Multi-Agent System Design Principles for Resilient Operation of Future Power Systems," in *IEEE International Workshop on Intelligent Energy Systems*, San Diego, CA, 2014, pp. 1–7. [Online]. Available: <http://amfarid.scripts.mit.edu/resources/Conferences/SPG-C42.pdf>
- [113] —, "Multi-Agent System Design Principles for Resilient Coordination & Control of Future Power Systems," *Intelligent Industrial Systems (in press)*, vol. 1, no. 1, pp. 1–9, 2015. [Online]. Available: <http://amfarid.scripts.mit.edu/resources/Journals/SPG-J17.pdf>
- [114] M. Amin, "Toward self-healing energy infrastructure systems," *Computer Applications in Power, IEEE*, vol. 14, no. 1, pp. 20–28, 2001.
- [115] —, "Toward a self-healing energy infrastructure," in *Power Engineering Society General Meeting 2006*, Montreal, Canada, 2006.
- [116] —, "Challenges in reliability, security, efficiency, and resilience of energy infrastructure: toward smart self-healing electric power grid," in *Power and Energy Society General Meeting 2008*, Pittsburgh, PA, USA, 2008, pp. 1–5.
- [117] S. M. Amin, "Smart grid Overview issues and opportunities. Advances and challenges in sensing modeling simulation optimization and control," *European Journal of Control*, vol. 17, no. 5-6, pp. 547–567, 2011. [Online]. Available: <http://dx.doi.org/10.3166/EJC.17.547-567>
- [118] S. D. J. McArthur, P. C. Taylor, G. W. Ault, J. E. King, D. Athanasiadis, V. D. Alimisis, and M. Czaplewski, "The Autonomic Power System - Network operation and control beyond smart grids," in *3rd IEEE PES Innovative Smart Grid Technologies Europe, ISGT Europe*, Berlin, Germany, 2012, pp. 1–7.
- [119] A. Kantamneni, L. E. Brown, G. Parker, and W. W. Weaver, "Survey of multi-agent systems for microgrid control," *Engineering Applications of Artificial Intelligence*, vol. 45, pp. 192 – 203, 2015. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0952197615001529>
- [120] C. N. Papadimitriou, E. I. Zountouridou, and N. D. Hatziaziyiou, "Review of hierarchical control in DC microgrids," *Electric Power Systems Research*, vol. 122, no. 0, pp. 159–167, 2015.
- [121] FERC and NERC, "Arizona-Southern California Outages on September 8 2011," Federal Energy Regulatory Commission and the North American Electric Reliability Corporation, Tech. Rep. 2, Jun. 2012. [Online]. Available: <http://www.ncbi.nlm.nih.gov/pubmed/23708957>
- [122] WECC, "Response to the "Arizona-Southern California Outages on September 8, 2011"," Western Electricity Coordinating Council, Salt Lake City Utah, Tech. Rep., 2012.
- [123] P. Martin, "The need for enterprise control," *InTech*, vol. Nov/Dec, pp. 1–5, 2012. [Online]. Available: <http://www.isa.org/InTechTemplate.cfm?Section=Archives4&template=/ContentManagement/ContentDisplay.cfm&ContentID=91325>
- [124] ANSI-ISA, "Enterprise Control System Integration Part 3: Activity Models of Manufacturing Operations Management," The International Society of Automation, Tech. Rep., 2005.
- [125] —, *Enterprise-Control System Integration Part 1: Models and Terminology*, ansi/isa-9 ed. Instrument Society of America, 2000, no. July.
- [126] L. M. Sanchez and R. Nagi, "A review of agile manufacturing systems," *International Journal of Production Research*, vol. 39, no. 16, pp. 3561–3600, 2001.
- [127] A. Gunasekaran, "Agile manufacturing: enablers and an implementation framework," *International Journal of Production Research*, vol. 36, no. 5, pp. 1223–1247, 1998.
- [128] R. Beach, A. P. Muhlemann, D. H. R. Price, A. Paterson, and J. A. Sharp, "Review of manufacturing flexibility," *European Journal of Operational Research*, vol. 122, no. 1, pp. 41–57, 2000. [Online]. Available: [http://dx.doi.org/10.1016/S0377-2217\(99\)00062-4](http://dx.doi.org/10.1016/S0377-2217(99)00062-4)
- [129] A. De Toni and S. Tonchia, "Manufacturing Flexibility: a literature review," *International Journal of Production Research*, vol. 36, no. 6, pp. 1587–1617, 1998.
- [130] H. J. Pels, J. C. Wortmann, and A. J. R. Zwegers, "Flexibility in manufacturing: an architectural point of view," *Computers in Industry*, vol. 33, no. 2-3, pp. 271–283, 1997.
- [131] E. Lalalus, S. G. Fang, C. Rang, and R. J. van Gerwen, "Manufacturing integration," *Computers in Industry*, vol. 27, no. 2, pp. 155–165, 1995.
- [132] T. J. Williams, G. A. Rathwell, and H. Li, *A Handbook on Master Planning and Implementation for Enterprise Integration Programs*. Purdue University Institute for Interdisciplinary Engineering Studies, 2001.
- [133] K. Kosanke, F. Vernadat, and M. Zelm, "CIMOSA: Enterprise engineering and integration," *Computers in Industry*, vol. 40, no. 2-3, pp. 83–87, 1999.
- [134] F. F. Wu, K. Moslehi, and A. Bose, "Power System Control Centers: Past, Present, and Future," *Proceedings of the IEEE*, vol. 93, no. 11, pp. 1890–1908, 2005.
- [135] Anonymous, "NIST Framework and Roadmap for Smart Grid Interoperability Standards Release 1.0: NIST Special Publication 1108," Office of the National Coordinator for Smart Grid Interoperability, National Institute of Standards and Technology, United States Department of Commerce, Washington D.C., Tech. Rep. NIST Special Special Publication 1108, 2010.
- [136] P. S. Moura and A. T. de Almeida, "The role of demand-side management in the grid integration of wind power," *Applied Energy*, vol. 87, no. 8, pp. 2581–2588, Aug. 2010. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0306261910000838>
- [137] P. Palensky and D. Dietrich, "Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads," pp. 381–388, 2011.
- [138] S. Emec, M. Kuschke, M. Chemnitz, and K. Strunz, "Potential for demand side management in automotive manufacturing," pp. 1–5, 2013.
- [139] M. Starke, D. Letto, N. Alkadi, R. George, B. Johnson, K. Dowling, and S. Khan, "Demand-side response from industrial loads," in *NSTI Nanotechnology Conference and Expo, NSTI-Nanotech 2013*, Washington, USA, 2013, pp. 758–761.
- [140] NERC, "Reliability Standards for the Bulk Electric Systems of North America," NERC–North American Electric Reliability Corporation, Tech. Rep., 2012. [Online]. Available: http://www.nerc.com/files/Reliability_Standards_Complete_Set_1Dec08.pdf
- [141] L. Soder and H. Holttinen, "On methodology for modelling wind power impact on power systems," *International Journal of Global Energy Issues*, vol. 29, no. 1-2, pp. 181–198, 2008.
- [142] H. Holttinen, M. O. Malley, J. Dillon, and D. Flynn, "Recommendations for Wind Integration Studies – IEA Task 25," International Energy Agency, Helsinki, Tech. Rep., 2012.
- [143] H. Holttinen, A. Orths, H. Abilgaard, F. van Hulle, J. Kiviluoma, B. Lange, M. O'Malley, D. Flynn, A. Keane, J. Dillon, E. M. Carlini, J. O. Tande, A. Estanquero, E. G. Lazaro, L. Soder, M. Milligan, C. Smith, and C. Clark, "IEA Wind Export Group Report on Recommended Practices Wind Integration Studies," International Energy Agency, Paris, France, Tech. Rep., 2013.
- [144] M. Milligan, K. Porter, E. DeMeo, P. Denholm, H. Holttinen, B. Kirby, N. Miller, A. Mills, M. O'Malley, M. Schuerger, and L. Soder, "Wind power myths debunked," *IEEE Power and Energy Magazine*, vol. 7, no. 6, pp. 89–99, 2009. [Online]. Available: <http://dx.doi.org/10.1109/MPE.2009.934268>
- [145] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Cañizares, N. Hatziaziyiou, D. Hill, A. Stankovic, C. Taylor, T. Van Cutsem, V. Vittal, C. Canizares, and T. Van Cutsem, "Definition and classification of power system stability," *IEEE Transactions on Power Systems*, vol. 19, no. 3, pp. 1387–1401, 2004. [Online]. Available: <http://dx.doi.org/10.1109/TPWRS.2004.825981>
- [146] S. Chakraborty, B. Kramer, and B. Kroposki, "A review of power electronics interfaces for distributed energy systems towards achieving low-cost modular design," *Renewable and Sustainable Energy Reviews*, vol. 13, pp. 2323–2335, 2009.
- [147] M. D. Ilic, "From Hierarchical to Open Access Electric Power Systems," *Proceedings of the IEEE*, vol. 95, no. 5, pp. 1060–1084, May 2007.
- [148] M. D. Ilić, L. Xie, U. A. Khan, and J. M. F. Moura, "Modeling of Future Cyber-Physical Energy Systems for Distributed Sensing and Control," *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on*, vol. 40, no. 4, pp. 825–838, 2010.
- [149] S. Rivera, A. M. Farid, and K. Youcef-Toumi, "Chapter 15 - a multi-agent system coordination approach for resilient self-healing operations in multiple microgrids," in *Industrial Agents*, P. L. Karnouskos, Ed. Boston: Morgan Kaufmann, 2015, pp. 269 – 285. [Online]. Available: <http://amfarid.scripts.mit.edu/resources/Books/SPG-B03.pdf>

- [150] National Energy Technology Laboratory, "A Compendium of Smart Grid Technologies: NETL Modern Grid Strategy Power our 21st-Century Economy," National Energy Technology Laboratory and the U.S. Department of Energy Office of Electricity Delivery and Energy Reliability, Tech. Rep. July, 2009.
- [151] S. A. Boyer, *SCADA- Supervisory Control And Data Acquisition*, 3rd ed. U.S.A: ISA, 2004.
- [152] A. G. Phadke, "Synchronized phasor measurements in power systems," *Computer Applications in Power, IEEE*, vol. 6, no. 2, pp. 10–15, 1993.
- [153] L. F. Ochoa, L. C. Cradden, and G. P. Harrison, "Demonstrating the capacity benefits of dynamic ratings in smarter distribution networks," in *Innovative Smart Grid Technologies (ISGT), 2010*. Gaithersburg, MD, United states: IEEE Computer Society, 2010, pp. 1–6. [Online]. Available: <http://dx.doi.org/10.1109/ISGT.2010.5434782>
- [154] W.-Q. Sun, Y. Zhang, C.-M. Wang, and P. Song, "Flexible load shedding strategy considering real-time dynamic thermal line rating," *Generation, Transmission & Distribution, IET*, vol. 7, no. 2, pp. 130–137, 2013.
- [155] B. Uluski, "Distribution Management Systems," EPRI, Cleveland, Ohio, Tech. Rep., 2011.
- [156] A. P. S. Meliopoulos, E. Polymeneas, Z. Tan, R. Huang, and D. Zhao, "Advanced Distribution Management System," pp. 2109–2117, 2013.
- [157] E. Mashhour and S. M. Moghaddas-Tafreshi, "Bidding Strategy of Virtual Power Plant for Participating in Energy and Spinning Reserve Markets—Part II: Numerical Analysis," pp. 957–964, 2011.
- [158] —, "Bidding Strategy of Virtual Power Plant for Participating in Energy and Spinning Reserve Markets—Part I: Problem Formulation," pp. 949–956, 2011.
- [159] O. Palizban, K. Kauhaniemi, and J. M. Guerrero, "Microgrids in active network management—Part I: Hierarchical control, energy storage, virtual power plants, and market participation," *Renewable and Sustainable Energy Reviews*, vol. 36, pp. 428–439, Aug. 2014. [Online]. Available: <http://linkinghub.elsevier.com/retrieve/pii/S1364032114000264>
- [160] E. F. Camacho and C. Bordons, *Model predictive control*, 2nd ed. London ; New York: Springer, 2007. [Online]. Available: <http://dx.doi.org/10.1007/978-0-85729-398-5MITAccessOnly>
- [161] N. G. Hingorani and L. Gyugyi, *Understanding FACTS : concepts and technology of flexible AC transmission systems*. New York: IEEE Press, 2000. [Online]. Available: <http://ieeexplore.ieee.org/xpl/bkabstractplus.jsp?bkn=5264253>
- [162] C. O. Adika and L. Wang, "Autonomous Appliance Scheduling for Household Energy Management," *Smart Grid, IEEE Transactions on*, vol. 5, no. 2, pp. 673–682, 2014.
- [163] E. Ela, M. Milligan, B. Parsons, D. Lew, and D. Corbus, "The evolution of wind power integration studies: Past, present, and future," pp. 1–8, 2009.
- [164] R. Gross, P. Heptonstall, D. Anderson, T. Green, M. Leach, and J. Skea, "The Costs and Impacts of Intermittency: An assessment of the evidence on the costs and impacts of intermittent generation on the British electricity network," Imperial College, London, UK, Tech. Rep., 2006.
- [165] NBSO, "Maritimes Area Wind Integration Study," Tech. Rep. August, 2005.
- [166] GE Energy, D. V. Zandt, L. Freeman, G. Zhi, R. Piwko, G. Jordan, and N. Miller, "Ontario Wind Integration Study," Tech. Rep., 2006.
- [167] P. Meibom, Risoe National Laboratory, R. Barth, H. Brand, H. Bernhard, D. Swider, and H. Ravn, "Final Report for All Island Grid Study Work-stream 2(b): Wind Variability Management Studies," Tech. Rep. July, 2007.
- [168] F. Rodriguez-Bobada, A. R. Rodrigues, A. Cena, and E. Giraut, "Study of wind energy penetration in the Iberian peninsula," Tech. Rep., 2006.
- [169] DENA, "Energy Management Planning for the Integration of Wind Energy into the Grid in Germany , Onshore and Offshore by 2020," Tech. Rep. February, 2005.
- [170] B. Hoflich, J. P. Molly, B. Neddermann, T. Schorer, D. Callies, K. Knorr, K. Rohrig, Y.-M. Sant-Drenan, U. Bachmann, R. Bauer, A. Konnemann, J. Muller, H. Radtke, I. August, E. Grebe, S. Groninger, C. Neumann, J. Runge, H. Abele, S. Jung, V. Schroth, O. Sener, S. Bopp, Y. Nguigan, M. Schmale, C. Siebels, W. Winter, F. Borggrefe, K. Grave, D. Lindenberger, C. Merz, M. Nicolosi, A. Nusler, J. Richter, M. Paulus, H. Samisch, J. Schwill, I. Stadler, J. Dobschinski, S. Faulstich, M. Puchta, and J. Sievers, "DENA Grid Study II: Integration of Renewable Energy Sources in the German Power Supply Systems from 2015-2020 with an Outlook to 2025," German Energy Agency, Berlin, Germany, Tech. Rep., 2010.
- [171] B. C. Ummels, "Power System Operation with Large-Scale Wind Power in Liberalised Environments," Ph.D. dissertation, Technical University of Delft, 2009.
- [172] U. Axelsson, R. Murray, V. Neimane, and ELFORSK, "4000 MW wind power in Sweden Impact on regulation and reserve requirements," Tech. Rep., 2005.
- [173] J. Bertsh, C. Growitsch, S. Lorenczik, and S. Nagl, "Flexibility options in European electricity markets in high RES-E scenarios Study on behalf of the International Energy Agency (IEA)," Institute of Energy Economics, Cologne, Germany, Tech. Rep. October, 2012.
- [174] EWIS, "European Wind Integration Study (EWIS) Towards A Successful Integration into European Electricity Grids Appendix," ENTOS-E, Brussels, Belgium, Tech. Rep., 2010.
- [175] F. V. Hulle, J. O. Tande, L. Warland, M. Korpas, P. Meibom, P. Sorensen, P. E. Morthorst, N. Cutululis, G. Giebel, H. Larsen, A. Woyte, G. Dooms, P.-A. Mali, A. Delwart, F. Verheij, C. Kleinschmidt, N. Moldovan, H. Holttinen, B. Lemstrom, S. Uski-Joutsenvuo, P. Gardner, G. van der Toorn, J. McLean, S. Cox, K. Purchala, S. Wagemans, A. Tiedemann, P. Kreutzkamp, C. Srikanand, and J. Volker, "Tradewind Integrating Wind – Developing Europe’s power market for the large-scale integration of wind power," European Wind Energy Association, Fredericia, DK, Tech. Rep., 2009.
- [176] G. Strbac, A. Shakoob, M. Black, D. Pudjianto, and T. Bopp, "Impact of wind generation on the operation and development of the UK electricity systems," *Electric Power Systems Research*, vol. 77, pp. 1214–1227, Jul. 2007.
- [177] I. Norheim, E. Lindgren, S. Uski, P. Sorensen, C. Jauch, and WILMAR, "WILMAR WP5-Deliverable D5.1 System stability analysis," Tech. Rep., 2005.
- [178] EnerNex, "Final Report Avista Corporation Wind Integration Study," Tech. Rep., 2007.
- [179] T. Mason, T. Curry, M. Hong, B. Joe, S. Olson, M. Sprouse, and D. Wilson, "SOLAR PHOTOVOLTAIC (PV) INTEGRATION COST STUDY," Black & Veatch, Overland Park, Kansas, Tech. Rep. 174880, 2012.
- [180] S. Venkataraman, G. Jordan, R. Piwko, L. Freeman, U. Helman, C. Loutan, G. Rosenblum, J. Xie, H. Zhou, and M. Kuo, "Integration of Renewable Resources: Operational Requirements and Generation Fleet Capability at 20% RPS," California-Independent System Operator, Tech. Rep., 2010.
- [181] EnerNex, "EASTERN WIND INTEGRATION AND TRANSMISSION STUDY," Tech. Rep. January, 2010.
- [182] GE Energy, "Final Report Analysis of Wind Generation Impact on ERCOT Ancillary Services Requirements," GE Energy for Electric Reliability Council of Texas, Tech. Rep., 2008.
- [183] University of Hawaii, "Oahu Wind Integration Study," University of Hawaii, Hawaii Natural Energy Institute, School of Ocean and Earth Science and Technology, Oahu, HA, Tech. Rep. February, 2011.
- [184] B. Johnson, J. Lindsay, K. Myers, P. Woods, and C. Yourkowski, "Solar Integration Study Report," Idaho Power, Tech. Rep. June, 2014.
- [185] D. Savage, "Final Report - 2006 Minnesota Wind Integration Study Volume I," EnerNex Corporation, Knoxville, TN, Tech. Rep., 2006.
- [186] EnerNex and NREL, "Nebraska Statewide Wind Integration Study," Tech. Rep. March, 2010.
- [187] GE Energy and GE-Energy, "New England Wind Integration Study," GE Energy, Schenectady, New York, Tech. Rep. May, 2010.
- [188] E. Shlatz, L. Frantzis, T. McClive, G. Karlson, D. Acharya, S. Lu, P. Etingov, R. Diao, J. Ma, N. Samaan, V. Chadliev, M. Smart, R. Salgo, R. Sorensen, B. Allen, B. Idelchik, A. Ellis, J. Stein, C. Hanson, Y. V. Makarov, X. Guo, R. P. Hafen, C. Jin, and H. Kirkham, "Large-Scale PV Integration Study," Navigant Consulting, Las Vegas, NV, USA, Tech. Rep., 2011.
- [189] R. Piwko, X. Bai, K. Clark, G. Jordan, N. Miller, and J. Zimmerlin, "The Effects of Integrating Wind Power on Transmission System Planning, Reliability and Operations," GE Energy, Schenectady, New York, Tech. Rep., 2005.
- [190] PACIFICORP, "Project Method for 2010 Wind Integration Cost Study," Tech. Rep., 2010.
- [191] GE Energy, "PJM Renewable Integration Study (PRIS) Project Review (Task 3a)," 2013.
- [192] Charles River Associates, "SPP WITF Wind Integration Study," Charles River Associates, Boston, MA, Tech. Rep., 2010.
- [193] GE Energy, "WESTERN WIND AND SOLAR INTEGRATION STUDY," Tech. Rep. May, 2010.
- [194] D. Lew, G. Brinkman, E. Ibanez, A. Florita, M. Heaney, B. Hodge, M. Hummon, G. Stark, and J. King, "The Western Wind and Solar Integration Study Phase 2," Tech. Rep. September, 2013.

- [195] E. A. DeMeo, W. Grant, M. R. Milligan, and M. J. Schuerger, "Wind plant integration," *Power and Energy Magazine, IEEE*, vol. 3, no. 6, pp. 38–46, 2005.
- [196] J. C. Smith, M. R. Milligan, E. A. DeMeo, and B. Parsons, "Utility Wind Integration and Operating Impact State of the Art," *Power Systems, IEEE Transactions on*, vol. 22, no. 3, pp. 900–908, 2007.
- [197] L. Bird, M. Milligan, and NREL, "Lessons from Large-Scale Renewable Energy Integration Studies Preprint," in *2012 World Renewable Energy Forum*, no. June, Denver, CO, United states, 2012, pp. –8.
- [198] H. Holttinen, M. Milligan, E. Ela, N. Menemenlis, J. Dobschinski, B. Rawn, R. J. Bessa, D. Flynn, E. Gomez-Lazaro, and N. K. Dettlesen, "Methodologies to Determine Operating Reserves Due to Increased Wind Power," *Sustainable Energy, IEEE Transactions on*, vol. 3, no. 4, pp. 713–723, 2012.
- [199] E. Ela, B. Kirby, E. Lannoye, M. Milligan, D. Flynn, B. Zavadil, and M. O'Malley, "Evolution of operating reserve determination in wind power integration studies," in *Power and Energy Society General Meeting, 2010 IEEE*, 2010, pp. 1–8.
- [200] H. Holttinen, M. Milligan, B. Kirby, T. Acker, V. Neimane, and T. Molinski, "Using Standard Deviation as a Measure of Increased Operational Reserve Requirement for Wind Power," *Wind Engineering*, vol. 32, no. 4, pp. 355–377, 2008. [Online]. Available: <http://dx.doi.org/10.1260/0309-524X.32.4.355>
- [201] A. Robitaille, I. Kamwa, A. Oussedik, M. de Montigny, N. Menemenlis, M. Huneault, A. Forcione, R. Mailhot, J. Bourret, and L. Bernier, "Preliminary Impacts of Wind Power Integration in the Hydro-Quebec System," *Wind Engineering*, vol. 36, no. 1, pp. 35–52, Feb. 2012. [Online]. Available: <http://dx.doi.org/10.1260/0309-524X.36.1.35>
- [202] T. Aigner, S. Jaehnert, G. L. Doorman, and T. Gjengedal, "The Effect of Large-Scale Wind Power on System Balancing in Northern Europe," *Sustainable Energy, IEEE Transactions on*, vol. 3, no. 4, pp. 751–759, 2012.
- [203] B. C. Ummels, M. Gibescu, E. Pelgrum, W. L. Kling, and A. J. Brand, "Impacts of Wind Power on Thermal Generation Unit Commitment and Dispatch," *IEEE Transactions on Energy Conversion*, vol. 22, no. 1, pp. 44–51, 2007. [Online]. Available: <http://dx.doi.org/10.1109/TEC.2006.889616>
<http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4106021>
- [204] D. A. Halamaj, T. K. A. Brekken, A. Simmons, and S. McArthur, "Reserve Requirement Impacts of Large-Scale Integration of Wind, Solar, and Ocean Wave Power Generation," *Sustainable Energy, IEEE Transactions on*, vol. 2, no. 3, pp. 321–328, 2011.
- [205] C. W. Hansen and A. D. Papalexopoulos, "Operational Impact and Cost Analysis of Increasing Wind Generation in the Island of Crete," *Systems Journal, IEEE*, vol. 6, no. 2, pp. 287–295, 2012.
- [206] D. L. Brooks, E. O. Lo, J. W. Smith, J. H. Pease, and M. McGree, "ASSESSING THE IMPACT OF WIND GENERATION ON SYSTEM OPERATIONS AT XCEL ENERGY – NORTH AND BONNEVILLE POWER ADMINISTRATION," 2002.
- [207] P. S. Georgilakis, "Technical challenges associated with the integration of wind power into power systems," *Renewable and Sustainable Energy Reviews*, vol. 12, pp. 852–863, 2008.
- [208] A. Muzhikyan, A. M. Farid, and K. Youcef-Toumi, "An Enhanced Method for the Determination of Load Following Reserves," in *American Control Conference, 2014*, Portland, Oregon, 2014, pp. 1–8. [Online]. Available: <http://dx.doi.org/10.1109/ACC.2014.6859254>
- [209] —, "An Enhanced Method for Determination of the Ramping Reserves," in *IEEE American Control Conference*, Los Angeles, CA, USA, 2015, pp. 1–8. [Online]. Available: <http://amfarid.scripts.mit.edu/resources/Conferences/SPG-C46.pdf>
- [210] —, "An Enhanced Method for Determination of the Regulation Reserves," in *IEEE American Control Conference*, Los Angeles, CA, USA, 2015, pp. 1–8. [Online]. Available: <http://amfarid.scripts.mit.edu/resources/Conferences/SPG-C47.pdf>
- [211] P. J. Luickx, E. D. Delarue, and W. D. D'haeseleer, "Effect of the generation mix on wind power introduction," *Renewable Power Generation, IET*, vol. 3, no. 3, pp. 267–278, 2009.
- [212] Y. V. Makarov, P. V. Etingov, J. Ma, Z. Huang, and K. Subbarao, "Incorporating uncertainty of wind power generation forecast into power system operation, dispatch, and unit commitment procedures," *IEEE Transactions on Sustainable Energy*, vol. 2, no. 4, pp. 433–442, 2011. [Online]. Available: <http://dx.doi.org/10.1109/TSTE.2011.2159254>
- [213] Y. V. Makarov, S. Lu, N. Samaan, Z. Huang, K. Subbarao, P. V. Etingov, J. Ma, R. P. Hafen, R. Diao, and N. Lu, "Integration of uncertainty information into power system operations BT - 2011 IEEE PES General Meeting: The Electrification of Transportation and the Grid of the Future, July 24, 2011 - July 28, 2011," in *Power and Energy Society General Meeting, 2011 IEEE*, ser. IEEE Power and Energy Society General Meeting. Pacific Northwest National Laboratory, Richland, WA 99354, United States: IEEE Computer Society, 2011, pp. 1–13. [Online]. Available: <http://dx.doi.org/10.1109/PES.2011.6039913>
- [214] Y. V. Makarov, C. Loutan, J. Ma, and P. de Mello, "Operational Impacts of Wind Generation on California Power Systems," *Power Systems, IEEE Transactions on*, vol. 24, no. 2, pp. 1039–1050, 2009.
- [215] M. H. Albadi and E. F. El-Saadany, "Comparative study on impacts of wind profiles on thermal units scheduling costs," *Renewable Power Generation, IET*, vol. 5, no. 1, pp. 26–35, 2011.
- [216] R. Billinton and G. Bai, "Generating capacity adequacy associated with wind energy," *Energy Conversion, IEEE Transactions on*, vol. 19, no. 3, pp. 641–646, 2004.
- [217] B.-M. Hodge, D. Lew, M. Milligan, H. Holttinen, S. Sillanpaa, E. Gomez-Lazaro, R. Scharff, L. Soder, X. G. Larsen, G. Giebel, D. Flynn, and J. Dobschinski, "Wind Power Forecasting Error Distributions: An International Comparison," in *11th Annual International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants Conference*. Lisbon, Portugal: National Renewable Energy Laboratory, 2012, pp. 1–9.
- [218] B.-M. Hodge, A. Florita, K. Orwig, D. Lew, and M. Milligan, "A Comparison of Wind Power and Load Forecasting Error Distributions," in *2012 World Renewable Energy Forum*. Denver, CO, United states: National Renewable Energy Laboratory, 2012.
- [219] B. Hodge and M. Milligan, "Wind Power Forecasting Error Distributions over Multiple Timescales," in *Power and Energy Society General Meeting, 2011 IEEE*. National Renewable Energy Laboratory, 2011, pp. 1–8.
- [220] J. A. Gubner, *Probability and Random Processes for Electrical and Computer Engineers*. Cambridge: Cambridge University Press, 2006.
- [221] E. Lannoye, D. Flynn, and M. O'Malley, "Evaluation of Power System Flexibility," pp. 922–931, 2012.
- [222] A. Tuohy and H. Chandler, "Flexibility assessment tool: IEA grid integration of variable renewables project," pp. 1–4, 2011.
- [223] ENTSO-E, "10-Year Network Development Plan 2012," ENTSO-E, Brussels, Belgium, Tech. Rep., 2012.
- [224] A. Muzhikyan, A. M. Farid, and K. Youcef-Toumi, "Variable Energy Resource Induced Power System Imbalances: A Generalized Assessment Approach," in *IEEE Conference on Technologies for Sustainability*, Portland, Oregon, 2013, pp. 1–8. [Online]. Available: <http://dx.doi.org/libproxy.mit.edu/10.1109/SusTech.2013.6617329>
- [225] —, "Variable Energy Resource Induced Power System Imbalances: Mitigation by Increased System Flexibility, Spinning Reserves and Regulation," in *IEEE Conference on Technologies for Sustainability*, Portland, Oregon, 2013, pp. 1–7. [Online]. Available: <http://dx.doi.org/libproxy.mit.edu/10.1109/SusTech.2013.6617292>
- [226] —, "An Enterprise Control Assessment Method for Variable Energy Resource Induced Power System Imbalances Part 1: Methodology," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 2448–2458, 2015. [Online]. Available: <http://amfarid.scripts.mit.edu/resources/Journals/SPG-J15.pdf>
- [227] —, "An Enterprise Control Assessment Method for Variable Energy Resource Induced Power System Imbalances Part 2: Results," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 2459–2467, 2015. [Online]. Available: <http://amfarid.scripts.mit.edu/resources/Journals/SPG-J16.pdf>
- [228] —, "A Power Grid Enterprise Control Method for Energy Storage System Integration," in *IEEE Innovative Smart Grid Technologies Conference Europe*, Istanbul, Turkey, 2014, pp. 1–6. [Online]. Available: <http://amfarid.scripts.mit.edu/resources/Conferences/SPG-C43.pdf>
- [229] —, "Relative Merits of Load Following Reserves & Energy Storage Market Integration Towards Power System Imbalances," *International Journal of Electrical Power and Energy Systems (in press)*, vol. 1, no. 1, pp. 1–8, 2015.
- [230] B. Jiang, A. Muzhikyan, A. M. Farid, and K. Youcef-Toumi, "Impacts of industrial baseline errors in demand side management enabled enterprise control," in *IECON 2015 – 41st Annual Conference of the IEEE Industrial Electronics Society*, 2015.
- [231] R. Podmore and M. R. Robinson, "The role of simulators for smart grid development," *IEEE Transactions on Smart Grid*, vol. 1, no. 2, pp. 205–212, 2010. [Online]. Available: <http://dx.doi.org/10.1109/TSG.2010.2055905>

- [232] F. J. D. Sisternes, S. Member, M. D. Webster, F. J. de Sisternes, M. D. Webster, and I. J. Perez-Arriaga, "The Impact of Bidding Rules on Electricity Markets With Intermittent Renewables," *Power Systems, IEEE Transactions on*, vol. 30, no. 3, pp. 1603–1613, 2015.
- [233] B. Jiang, A. M. Farid, and K. Youcef-Toumi, "A comparison of day-ahead wholesale market: Social welfare vs industrial demand side management," in *IEEE International Conference on Industrial Technology*, Sevilla, Spain, 2015, pp. 1–7. [Online]. Available: <http://amfarid.scripts.mit.edu/resources/Conferences/SPG-C44.pdf>
- [234] —, "Impacts of industrial baseline errors on demand side management in day-ahead wholesale markets," in *Proceedings of the ASME Power & Energy 2015: Energy Solutions for Sustainable Future*, San Diego, CA, 2015, pp. 1–7.
- [235] —, "Demand side management in a day-ahead wholesale market: A comparison of industrial & social welfare approaches," *Applied Energy (in press)*, 2015.
- [236] A. M. Farid, "Electrified transportation system performance: Conventional vs. online electric vehicles," in *Electrification of Ground Transportation Systems for Environment and Energy Conservation*, N. P. Suh and D. H. Cho, Eds. MIT Press, 2015, ch. 22, pp. 1–25.
- [237] W. C. Schoonenberg and A. M. Farid, "A dynamic production model for industrial systems energy management," in *2015 IEEE International Conference on Systems Man and Cybernetics*. Hong Kong, 2015, pp. 1–7.