The Need for Holistic Assessment Methods for the Future Electricity Grid

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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 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 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 reliability consequences. This work, thus, 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 presentation concludes with a reconfigurable framework for power grid analysis 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. The first of these is decarbonization [6]. The European Union, for example, has committed to reduce greenhouse gas emissions in the power sector to 1990 levels by 2050 [7]. Such targets create a strong pressure for renewable energy penetration in both the transmission as well as the distribution system [8]. Next, electricity demand continues to grow sometimes as fast as 10% per year in the quickly developing economies [9], [10]. 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], [11]–[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], [18]. This transportation electrification driver requires the electrical grid to be fit for a new, significant and previously un-envisioned purpose [19]–[22]. 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 [23]. Finally, these deregulation trends have inspired and empowered consumers who respond to both physical and economic grid conditions [13]. 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 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 [24], it is less than clear how the holistic behavior of the grid will change or whether reliability will be assured. Furthermore, it is unclear what value for cost these control technologies can bring and what degree of control, automation, and information technology is truly necessary to achieve the desired level of reliability. 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 control technologies.

This argument is fashioned as follows. Section II describes the evolution of the grid in terms of the integration of variable energy resources and the subsequent changes in grid structure and behavior. Next, Section III reviews potential new control technologies and how they may be used to support enhanced operations. Next, Section IV briefly discusses the potential adequacy of existing assessment methods. In Section V, a reconfigurable framework for power grid analysis is proposed and Section VI concludes with the potential for new directions of active research and development.

II. BACKGROUND: EVOLUTION OF THE POWER GRID

The emergence of new drivers in the power grid is likely to alter the traditional trajectory of incremental improvements. Increasing concerns about power grid environmental impact and operations reliability motivate 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.

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 [25].

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 [7]. In the future, the choices of energy source are likely to be constrained by environmental considerations and not just simply technological limitations and resource scarcity. The European Union Emissions Trading scheme has imposed a price for carbon credits for power generation facilities [8], [26]. 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 oil 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 [27]. The first interest towards renewable sources of energy emerged after the oil crisis in 1970s, leading to some investments

TABLE I
THE POWER GRID OUTAGE STATISTICS

	Period	Occurrences of 100 MW or more	Occurrences of 50,000 or more consumers
NERC	1991-1995	66	41
	1996-2000	76	58
	2001-2005	140	92
EIA	2000-2004	156	149
	2005-2009	264	349

in their technological development [28]. However, after the decline of oil and gas prices during 1980s, renewable energy sources lost their competitive strength. Currently, the installation of renewable energy sources are mainly supported by governmental mandates and regulatory foundations such as Renewable Portfolio Standards [29]–[31].

Power grid reliability enhancement is a 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 [32]. A disparity between electricity demand and electric power infrastructure growths makes the North American electricity infrastructure increasingly stressed, and further aggravates reliability concerns. Table I 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 [25].

Decarbonization has led to a third driver: namely transportation electrification. The American transportation sector accounts for approximately two-third of the U.S. fossil fuel demand [33]. 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 [34], although its market will take time to develop [35], [36]. Despite the decarbonization advantages, the electrification of transport increases the dependence on the electricity grid [19]–[22]. 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 [19], [21]. 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 [37]. 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 [38]–[40]. 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 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 [41], [42] and power line carriers (PLC) [43] into the grid has facilitated communication with consumers and empowered them to make decisions based on the real-time grid conditions [41]–[45]. These enabling technologies allow demand to migrate from a passive, non-dispatchable behavior to one that is response to dynamic prices and reliability signals [12]. 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 [46], [47]. Furthermore, those power system operators that have implemented price-responsive demand-side management require complete visibility to energy resources [48]. 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 [49]. Since 1978, this vertically integrated value chain has become increasingly unbundled to allow for diversified and competitive wholesale transactions [23], [50]–[56]. 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 power system in the form of integration of variable energy resources, demand side management and electrified transport.

B. Characteristics of Variable Energy Resources

The five drivers, discussed in the previous section, demonstrate the strong role of variable energy resources, demand side management and electric vehicles 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

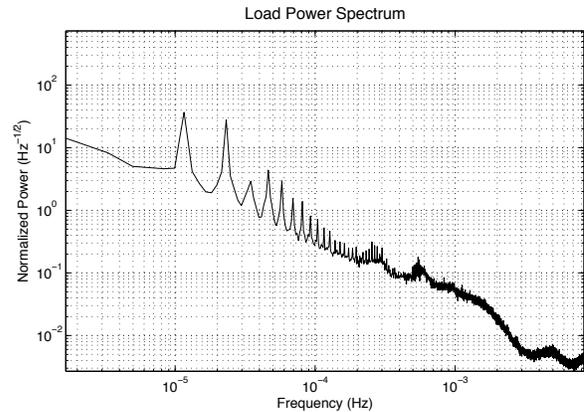Fig. 1. Traditional Grid Generation and Demand Portfolio [57]

Fig. 2. Normalized power spectrum of daily load (Data from Bonneville Power Administration)
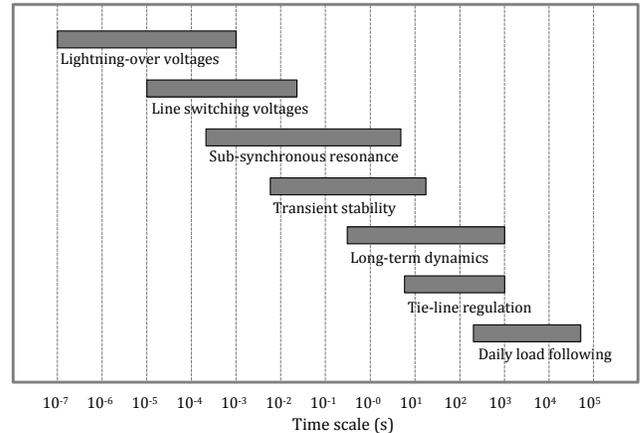

Fig. 3. Time scales of relevant power system dynamics [58]

As shown in Figure 1, 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 2. 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 [59]. These multiple time scales

excite and affect the different behavioral phenomena in the power grid shown in Figure 3. 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]. Over time, load became highly predictable with the state of the art being approximately 3% [60]. [58] error. On the supply side, the economic and regulatory structure drove power generation facilities towards economies of scale [61]. Consequently, different types of generation fulfilled different parts of the load: large coal/nuclear power plants supply the base load, CCGT units follow the changing load, and IC/GT come online during the peak load [4]. In summary, Figure 1 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 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. 4.   Future Grid Generation and Demand Portfolio [57]

The drivers described in the previous section change the picture of the generation and demand portfolio to the more balanced one shown in Figure 4. 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 [32]; 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 and electrical vehicles 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 [32]. Relative to traditional load, VER forecast accuracy is low, even in the short term [62]. There are two major groups of wind forecasting techniques: numerical weather prediction (NWP) and statistical methods [63]. 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 and electric vehicles have a stochastic nature from the perspective of power grid operator. In short, Figure 4 demonstrates a grid in which generation and supply are on
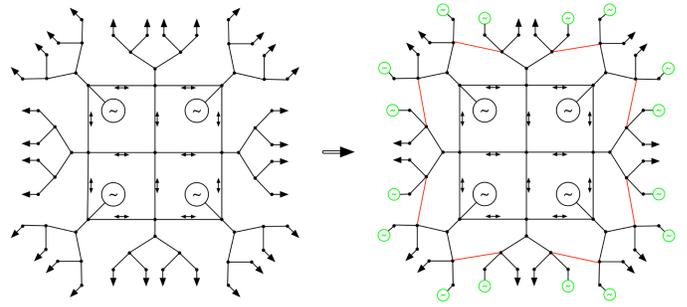

Fig. 5.   Graphical Representation of the Evolving Power Grid Structure [57]

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.

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, 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. Fig. 5 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 [64]. The protection system has to be redesigned accordingly [65], [66]. 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 and potentially effacing the clear separation between transmission and distribution. 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

The various power grid phenomena shown in Figure 3 have induced a traditional hierarchical control structure strictly separated by time scale. Ilic and Zaborsky classify this hierarchy as primary, secondary and tertiary [67]. Primary control addresses transient stability phenomena in the range of approximately 10-0.1Hz [68]. Generator output adjustments on

this time scale are performed by the implementation of local automatic control techniques such as automatic generation control, (AGC) and automatic voltage regulator (AVR) [5]. The former responds to fast imbalances between generation and consumption, while the latter responds to changes in generator output voltage [69]. 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 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 minimized the total operational cost of the system subject 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 blurs the distinction between control technique time scale. Recent reviews summarize the impact of VER integration [70] and [71], and a spectral characterization of both wind [59] and solar generation [72] has been conducted to show that VER integration affects all time scales of power system balancing operations. In response, the Federal Energy Regulatory Commission (FERC), has recently changed its requirements on minimal re-dispatch frequency from 1 hour to 15 minutes [73]. 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 [74]. In the meantime, the introduction of grid-scale storage [75] [37], smart buildings [76] [77], and fast ramping generation facilities [78] [79] expands the scope of transient stability studies into slower time scales dominated by dynamic poles in the hydraulic and thermal energy domains. In short, the traditional dichotomy of primary, secondary, and tertiary control is increasingly blurred with the penetration of VERs. Mathematically, the overlapping control techniques can be viewed as a *convolution* of actions which would necessitate holistic assessment methods.

The introduction of mesh networks in the distribution system shown in Figure 5 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 [69]. 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 configura-

tions may not be so [80]. Furthermore, many of the control theory concepts such as controllability and observability are inadequate for hybrid systems [81]. 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, self-healing power grids that respond to disturbances and contingencies [82]–[87]. In contrast, the San Diego Blackout of September 8 2011 is a reminder of the importance of even routine switching decisions [88], [89].

In conclusion, the need for holistic assessment methods is a consequence of the evolution of the 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 4 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 GRID ENTERPRISE CONTROL STRATEGY AND TECHNOLOGIES

The previous sections demonstrated a number of evolving trends which suggest a necessary rethink of holistic power system assessment and control. First, generation and demand are set to take much more equal responsibility over power grid operation. This appears in the degree of stochasticity but also in the degree of dispatchability. Furthermore, the combination of these two properties suggest a grid that is generally more dynamic in nature, and so requires greater attention to ramping capabilities and voltage stability. This section raises the concept of integrated enterprise control [90] as a holistic strategy and then briefly mentions the emerging technologies set to bring about such a strategy.

A. Grid Enterprise Control Strategy: Enabling Holistic Dynamic Properties

The ongoing evolution of the power grid can already be viewed through the lens of enterprise control. Originally, the concept of enterprise control [90] developed in the manufacturing sector out of the need for greater agility [91], [92] and flexibility [93]–[95] 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 [96] that control with business objectives. Over time, a number of integrated enterprise system architectures [97], [98] were developed coalescing in the current ISA- S95 standard [99]. Analogously, recent work on power grids has been proposed to update operation control center architectures [100] and integrate the associated communication architectures [42]. The recent NIST interoperability initiatives further demonstrate the trend towards integrated and holistic approaches to power grid operation [101]. These initiatives form the foundation for further more advanced holistic control of the grid [82], [102].

Fig. 7.   Integrated Enterprise Control of the Power Grid

	Generation	Demand
Dispatchability	• Low – Wind, Solar, Run of River Hydro • Medium – Hydro, Solar CSP • High – Thermal Units	• Low -- Lighting • Medium – HVAC, Commercial buildings • High -- Industrial production
Flexibility/Ramping (Thermal Energy to Work ratio)	• Low – Nuclear & Coal • Medium – CCGT • High – Hydro, GT, IC	• Low – Chemical, petrochemical, metals • Medium – HVAC, Commercial Buildings, Refrigerators • High – Heaters, kettles, EV battery
Forecastability	• Low – Solar PV • Medium – Wind generation • High – All dispatchable generation	• Low – N/A • Medium – lighting, cooking, hair drying • High – Scheduled Industrial Production
Voltage Stability	• Synchronous Generators w/ AVR • Wind Induction Generators w/ low voltage ride through • Solar PV w/ power electronics	• Synchronous motors in HVAC applications • Induction Motor appliances with active harmonic control • EV's w/ power electronic based control

Fig. 6.   Grid Enterprise Control to Enable Holistic Dynamic Properies

These integrative initiatives are the first step towards power grid operation that is founded upon the fusion of reliability and economic objectives. To that effect, the future electricity grid, with all of its new supply and demand side resources, must holistically enable its dynamic properties. Figure 6 shows the balanced role of generation and demand in regards to four dynamic control properties: dispatchability, flexibility, forecastability and voltage control.

Addressed holistically, different components of the power generation and demand have differing levels of dispatchability. While thermal generation has traditionally fulfilled this role, it is not unlikely that electricity-intensive industrial production can serve the counterpart role. 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 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.

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. Using another pareto analysis, one sees that ramping capabilities are often very much tied to the ratio of stored thermal energy to mechanical work. Facilities with a very large ratio
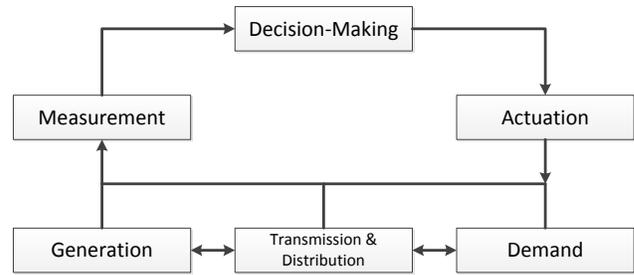
such as nuclear, coal, chemicals and metals have relatively low ramping capabilities. In contrast, facilities with a high ratio such as hydroelectric, gas turbines, internal combustion engines, heaters and kettles can easily ramp. The integration of VERs is a challenge not just because of their lack of dispatchability but because the stochastic nature can cause ramps of various *speeds* and not just magnitude.

The aggregate dispatchability and flexibility must also able to meet the lack of forecast ability 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. Such imbalances create a volatile situation which requires ever-more frequent and costly manual actions in concert with automatic generation control.

This more dynamic mode of operation must also not neglect voltage stability [103], [104]. To maintain this control objective, many types of generation and demand resources can potentially contribute to voltage support. Recent literature advocates a highly decentralized approach to the responsibility of voltage stability [105], [106].

B. Grid Enterprise Control Technology Integration

The four holistic dynamic properties of dispatchability, flexibility, forecast ability, and voltage stability taken greater importance in the context of the vast number of emerging "smart-grid" technologies entering the market [107]. 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 7. While an in- depth review [107] 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.

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 [108], as a well-established transmission technology is quickly entering distribution. In complement, smart meters [41], [42], phasor measurement units [109], and dynamic line ratings [110] 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 [111]. An extension of these is facility energy management systems which can integrate to the power grid [112]. 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 demand [113]. To that effect, model predict control techniques [114] have advanced significantly to support both individual as well as groups of facilities, be they for power generation or industrial production. FACTS devices [115] 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 appliance of nearly every type [41], [42].

In conclusion, the concept of enterprise control provides a working framework upon which to build holistic approaches to assessment and control. Such an approach can facilitate methods that directly address the four holistic dynamic properties discussed: dispatchability, flexibility, forecastability, and voltage stability. 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

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 [64] [5]. 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 [24]. A full review of these is certainly intractable and well beyond the scope of this work. Furthermore, the rationale presented in this paper advocates the enhancement 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. To that effect, numerous renewable energy integration studies have emerged in the academic and industrial literature [116]. Amongst these, wind power has attracted relatively more attention given its greater environmental potential in the geographies committed to renewable energy integration. Although references [117], [118] summarize the key points of the most prominent integration studies, the interested reader is referred to [116] for a more comprehensive list. This section summarizes the key conclusions of these works and presents some of their limitations that would motivate the need for more holistic assessment methods.

The main conclusion of these renewable integration studies is that intermittency and uncertainty will increase reserve requirements in the power system; and consequently increase the marginal cost power system operations [117], [118]. The exact degree of additional operational costs ultimately depends greatly on system properties such as generation mix and fuel cost. In contrast, one reference states that wind power variability will not have much impact on the operations because power grid operators already have experience in dealing with variability in the load. The inconsistency of the results can be attributed to the use of different methodologies, data, and assessment metrics.

Prior to discussing the limitations of these works, and given that much of the discussion centers around reserves management, it is important to recognize that each integration study uses its own terminology and classification of power system reserves depending on the region of interest. This work uses the classification of reserves found in [119], [120]. Two major types of reserves are discussed: event-based and non-event-based reserves. Event-based reserves respond to contingencies in the system and are also named contingency reserves. 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. 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 [119]. Non-event-based reserves are further classified by their response times: load following reserves handle intra-hour variations, and regulation reserves handle minute-to-minute variations of the net load. Both types can respond upwards and downwards. The conclusions concerning these non-event reserves is the focus of this review.

Generally speaking, integration studies use variations of the statistical methods found in [121] to estimate the the load following and regulation reserve requirement. The standard deviation of potential imbalances, σ, is calculated using the probability distribution of net load *or* forecast error. 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 standards. Normally, load following is taken equal to 2σ [121], [122] 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% [123]. This corresponds to 2σ for a normal distribution. Other integration studies have used a 3σ confidence interval [124], [125] to correspond to the industry standard of 95% [126]. Based on the experience of power system operators, regulation is normally taken to be between 4σ and 6σ [121], [122], [127].

The first limitation of this approach is the lack of consensus of whether to use the probability distribution of the net load or that of the forecast error. 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.

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 rarely considered in the literature. In [121], 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 [124] 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 [126] 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.

Another concern over operating reserve quantities and their timescales arises when considering the power system's operating procedures and control techniques. 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. 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 [62], [128], [129]. This assumption can be justified using the central limit theorem [130] 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 changes.

Of these limitations, one of the most evident is the lack of a holistic assessment approach. Many integration studies are only limited to statistical calculations and their results are not validated by simulation [120], [131]. Of these, some are limited to considering either only variability of the net load [121], [127], [132] or only its forecast error [125], [133]–[135]. Furthemore, not all studies consider the different timescales of operation. Reference [126] does not consider regulation because the available data has 10 minute resolution. Those wind power integration studies that do use simulation usually do so for a particular study area [136]. References [131], [132] implement only unit commitment models, according to the assumption that wind integration has the biggest impact on unit commitment.

In summary, a review of the existing literature on imbalance assessment methodologies shows a lack of holistic methods. Most of the studies consider the impact of only a few factors on the imbalances of the system, which can give only a partial picture of imbalances. Also, not all the control components are considered, sometimes limited to only unit commitment. The system balancing should be studied with the implementation of all relevant enterprise control functions in the coupled timescales so as to lead to reasonable results. Moreover, most of the studies are limited to statistical calculations, which are yet to be validated by simulations. Finally, many of the calculations are based upon the experience of system operators which may not necessarily remain valid as the power system continues to evolve.

V. Reconfigurable Framework for Holistic Power Grid Assessment

To address the literature gap identified in the previous section, the authors proposed a reconfigurable framework for the holistic assessment of the power grid. 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
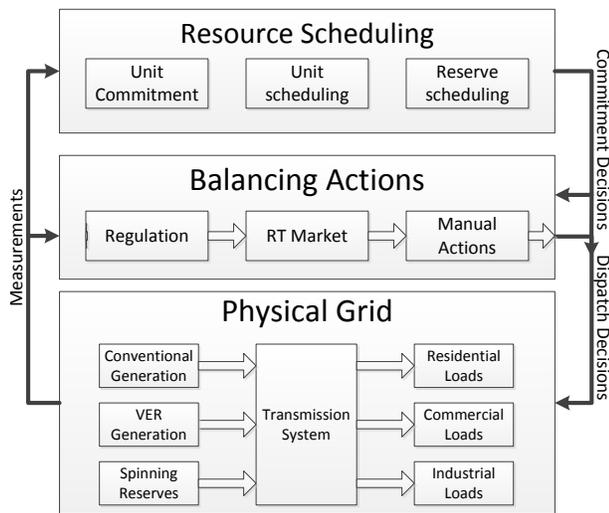
Fig. 8. Conceptual design of a power gr

- 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 and voltage stability
- represents potential changes in enterprise grid control functions and technologies as impacts on these dynamic properties.

The first five of these requirements are basically associated with the nature of the power grid itself as it evolves. In the meantime, the last two are associated with the behavior of the power grid in the operations time scale. To that effect, Figure 8 represents a conceptual design of a reconfigurable power system simulator that implements enterprise control. The simulator includes the physical electrical grid layer and incorporates primary, secondary and tertiary control layers. These layers may be modified as necessary to assess the impact of control function and technology on the time domain simulation.

One main advantage of this approach is that 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 implemented to systematically study the evolution of power system imbalances in relation enterprise control functions typically found in American transmission systems [137], [138].

VI. Conclusions

This paper has presented a 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 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 reliability consequences. This work, thus has motivated 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 presentation concludes with a reconfigurable framework for power grid analysis that is based upon seven requirements distilled from the discussions. Initial demonstrations of this framework are already reported and more holistic power system studies are envisioned.

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