Toward Standards for Dynamics in Electric Energy Systems

Future Grid Initiative White Paper

Power Systems Engineering Research Center

Empowering Minds to Engineer the Future Electric Energy System

Toward Standards for Dynamics In Electric Energy Systems

The Future Grid to Enable Sustainable Energy Systems
Funded by the U.S. Department of Energy

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PSERC Publication 12-09

June 2012

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Power Systems Engineering Research Center

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Acknowledgements

This white paper was developed as one of nine broad analysis white papers in the project "The Future Grid to Enable Sustainable Energy Systems: An Initiative of the Power Systems Engineering Research Center." This project is funded by the U.S. Department of Energy. More information about the Future Grid Initiative is available at the website of the Power Systems Engineering Research Center (PSERC), www.pserc.org. This white paper is in the broad analysis area "Grid Enablers of Sustainable Energy Systems."

The author greatly acknowledges several discussions with Dr. Bruce Fardanesh at New York Power Authority; with Dr. George Arnolds at National Institute of Standards (NIST); early discussion with Mahendra Patel at PJM; early discussion with Professor Ian Dobson at Iowa State University; recent feedback by Professors David Hill at the University of Sidney, Australia, Steven Low at the California Institute of Technology, Jeffrey Lang at M.I.T, and Munther Dahleh at M.I.T, and Le Xie and P.R. Kumar from Texas A&M University. The discussions with Qixing Liu, Carnegie Mellon University doctoral student in the Electrical and Computer Engineering Department whose PhD thesis concerns dynamics of future electric energy systems is also greatly appreciated.

The proposed standards for dynamics in this white paper are fundamentally based on the concept of structure-based modeling and control in complex electric power systems. The author's realization that this approach can be used to identify possible weaknesses with today's best practices and standards for dynamics; to propose relatively simple principles for provable control in complex electric power systems; and to, eventually utilize these for proposing principles for standards for dynamics is a result of many collaborations, too numerous to list individually. Nevertheless, special thanks go to late Professor John Zaborszky and his observation decoupled state space ideas; to Dr. Shell Liu, a former PhD student at M.I.T. through whose work the first idea of generalizing area control error to a dynamic interaction variable was borne; and, to Dr. Jeffrey Chapman, a former PhD student at M.I.T. whose graduate work on nonlinear control and feedback linearization was instrumental to proposing and simulating the decentralized stabilization of inter-area oscillation in the NPCC system. In our Electric Energy Systems Group (EESG) http://www.eesg.ece.cmu.edu/ and the Semiconductor Research Corporation Smart Grid Research Center (SRC SGRC) (home in EESG as part of the larger SRC Energy Research Initiative (SRC ERI) http://www.src.org/program/eri/) many students are pursuing their research using the structure-based modeling approach described in this white paper. Most recently, we have derived models and control design using this structure-based modeling approach to simulate how it would be, indeed, possible to have low-cost green solutions to electricity services in the Azores Islands, Portugal, to appear as a Springer Monograph entitled ``Engineering IT-Enabled Sustainable Electricity Services: The Tale of Two Low-Cost Green Azores Islands". The author greatly appreciates the synergic collaboration in EESG.

Executive Summary

This white paper concerns difficult questions regarding standards for dynamics of future electric energy systems. The electric power systems of today already have a well-defined physical structure and the design of future standards must evolve around the existing best practices. The emphasis is on identifying what might become possible problems with system dynamics as unconventional technologies are integrated into the existing T&D large-scale electric power grids, and how to design standards for dynamics which support system evolution without experiencing near real-time operating problems. The main challenge in introducing standards for dynamics is whether it is possible to design easy-to-use standards which will enable integration of new generation, T&D and demand technologies in a plug-and-play way without creating operating problems. Fast automation is key to managing hard-to-predict deviations of power generation, demand and transfers from their schedules in between the dispatch intervals. Standards for dynamics are needed to support this automation for ensuring safe and stable service.

In this paper we attempt the question of designing easy-to-implement standards for dynamics by first assessing what is available today. Based on this review we conclude that the existing standards for governor and excitation system response, along with the standards for automatic generation control (AGC) and/or for European automatic voltage control (AVC), are control area-level requirements which are not system specific. As such, they serve as a great starting point for what is needed in the future. We identify the assumptions underlying today's standards and their propose possible generalizations that relax these assumptions. It is notable that there are effectively no standards for dynamics in place for electricity users nor for rapidly growing deployment of Flexible AC Transmission Systems (FACTS). It is also notable that special purpose controllers which have been implemented for transient stabilization do not have quantifiable standard requirements for their dynamic performance. We illustrate dynamic problems in today's industry. We point out that these problems with system dynamics can be directly related to the assumptions made in today's best practice which do not hold in the examples discussed.

Throughout this paper we make every attempt to identify problems and propose principles for possible solutions using the same unifying structure-based modeling approach. This approach enables one to model system dynamics in terms of dynamics of local components and their explicit interactions with the system to which they are connected. This modeling approach lends itself to starting from the standards for dynamics presently used by the industry, and to identifying possible ways for generalizing these. We illustrate how by identifying this inherent structure deeply embedded in the physical design and organization of electric power grids the same examples of dynamic problems can be converted into examples of designing standards for ensuring no dynamic problems.

Based on the examples of past problems and the proposed structure-based modeling approach to automation design necessary to eliminate these problems, we propose a set of general principles which should underlie the design of standards for dynamics in the evolving electric energy systems. Three qualitatively different approaches are recommended.

1. First, the simplest, entirely plug-and-play standards design for dynamics requires that each (group of) components has sufficient adaptation to stabilize itself and to cancel the interaction variables with the neighboring (groups of) components. This is a simple design, yet, it is based on sufficient conditions and as such it is conservative with respect to the control requirements. Nevertheless, it can work and it can open doors to major innovation.
2. Second, standards for dynamics are proposed by which each (group of) components stabilizes its own dynamics and participates in minimal coordination of interaction variables managed at the higher system layer. Minimal coordination protocol is designed for careful trade off between the system-level response and cost of system-level control. As such, it is near-optimal, but requires protocol for coordination. We illustrate major gains from such minimal coordination. With the influx of synchrophasors, this is feasible to implement and it amounts to system-level wide area measurement systems (WAMS)-based coordination of dynamic interactions between the (groups of) components. A potential problem with this scheme is that it is not possible to uniquely assign the responsibility to specific (groups of) components nor is it possible to provide economic incentives for participating in higher-layer dynamic coordination.
3. To overcome the problem just noted, we propose a third possible framework for interactive participation protocol in system-level coordination. This protocol relies on exchanging information about component's willingness to contribute to coordinated control of interaction variables at the price range defined by the component to reflect unique control technology. We refer to this framework as the dynamic monitoring and decision systems (DYMONDS) protocol. We identify open research and development questions for all three possible pathways to standards for dynamics in future electric energy systems.

There have been many efforts over the past several years which are targeted to establishing architectures for smart grids, and these are referred to in this white paper. Also, recent efforts toward common information model (CIM) have been under way by focusing on standards design for characterizing the specifications of existing and new equipment in the power grids. The main objective of NIST standards of this type has been to enable deployment and integration of equipment made by different manufacturers in future electric energy systems. This goes a long way toward enabling analysis of systems as they evolve. This white paper complements these efforts by focusing specifically on standards for dynamics. The goal is to arrive at relatively simple standards and/or protocols which allow flexibility in technology used to meet them, and, at the same time, lead to provable and quantifiable performance and justification for such standards. To move forward to establishing such standards, it is important to have a systematic computer-aided approach for modeling, and demonstrating, at least by using simulations, that the proposed standards will meet their purpose.

Our general recommendation is to present and discuss the envisioned standards for dynamics with NERC, NIST, NASPI, IEEE and IEC and seek their comments. All these bodies should have a genuine interest and responsibilities in working toward standards for dynamics. The second recommendation is to consider an industry-academia team with a focused effort toward formalizing and adopting standards for dynamics.

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I. INTRODUCTION

At present there is much work under way which is pointing in the direction of distributed decision making for balancing forecast supply and demand. Knowledge is being acquired on how sub-optimal this process might be relative to fully centralized economic dispatch and unit commitment by the system operators. It is evident that coordinated resource scheduling over the broad ranges of system conditions remains necessary for ensuring that power schedules are deliverable across vast nonlinear electric power grids. Moreover, it is essential to have fast automation in place to ensure safe, stable and acceptable quality of service to manage hard-to-predict deviations of power generation, demand and transfers from their schedules in between the dispatch intervals. Standards for dynamics are needed to support this automation.

This white paper concerns, more specifically, standards for dynamics in future electric energy systems. As the industry evolves and new technologies mature, the historical boundaries between the dynamics and steady-state driven by the adaptations to system conditions are becoming truly gray. [1] This paper poses the objectives of standards for dynamics in a broader context of the electric energy industry standards, and even broader IEEE and IEC standards. The main challenge identified is the design of a systematic platform for enabling seamless integration of new technologies which will support dynamic specifications at different system layers; these range from the component level specifications, to aggregated groups of components interconnected via electric power grids (smart balancing authorities-SBAs) and, ultimately, to the dynamic specifications of the system as a whole. Also, standards are needed for integrating hybrid cooperative portfolia closer to the end users and at the distribution level, and to account for their effects by the balancing authorities responsible for operating the system at the higher level. The ultimate challenge comes from the need to define component-level standards which would ensure desired performance at the higher system levels. Given that the power grid network is highly nonlinear, it is fundamentally necessary to have standards which require automation to adjust to the changing operating conditions. This makes it very challenging to meet the provable performance requirement.

An important observation is that standards are needed for provable performance, and best effort approaches are not acceptable. The challenge of designing standards/protocols which have both provable and easy-to-implement characteristics is very hard. In this paper we propose that such design may be doable, once it is understood what needs fixing and why. We proceed by reviewing today's standards and best practices for dynamics in today's industry. This is important because the best outcome would be to build on the existing practices by enhancing them. We also illustrate several representative system-level problems with dynamics, and identify why these occurred. We proceed by observing that the conceptual interpretation of the existing standards, problems with system-level dynamics and a possible approach to systematic standard design for dynamics can all be tackled using our unifying structure-based modeling of electric power system dynamics. Both the existing and future electric energy systems lend themselves to this modeling approach.

Recently, models and control design using this structure-based modeling approach has been

[1] In this paper we use the term steady-state as a proxy for quasi-stationary moving equilibrium processes. This is done because of industry's common usage of the first term. We point out, however, that an electric power system is never at an equilibrium, and for understanding market-induced volatilities, for example, it is critical to begin to think of dispatch and intra-dispatch as event driven-process which may be stable or not.

used to simulate how it would be, indeed, possible to have low-cost green solutions to electricity services in the Azores Islands, Portugal [1]. This modeling approach is fundamentally scalable, and we are proposing to explore its potential for systematic integration of smart technologies to enable sustainable electricity services in continental interconnection system which have experienced dynamical instabilities caused by the high presence of intermittent resources.

We start in Section II by providing a short summary of related on-going efforts for standardization in the changing industry, in particular in the context of smart grid architecture designs.

In Section III we propose four different functionalities which standards for dynamics in complex network systems, such as the future electric energy systems, should meet.

In Section IV we assess the role of today's industry standards for power system dynamics in the context of these objectives. Operating problems in the past related to problems with meeting some of these objectives are briefly summarized. We provide several examples of why today's standards will not be sufficient to facilitate systematic innovation in the changing industry. We identify several major issues and illustrate them using small power system examples with embedded new technologies.

In Section V we briefly summarize the underlying structure inherent in the electric power systems dynamics and its models. We refer to this structure throughout the rest of the paper. We introduce a model-based mechanism for characterizing interactions between different (groups of) system components and for mathematically posing the objectives of standards for dynamics. The model of an evolving future electric energy system can be thought of in terms of these interaction variables. We suggest that re-thinking the objectives of the future electric energy systems can be made transparent by means of the modeling approach adopted here. In particular, we point out that the notion of dynamic interaction variables is a natural extension of the well-understood quasi-stationary concept of Area Control Error (ACE) and its further generalization proposed some time ago to account for electrical distances within a control area [2], [3].

In Section VI we introduce a mathematical definition of interaction variables and point out that this concept directly follows from relaxing asumptions when defining area control error (ACE) used today in automatic generation control (AGC). As such, it can be used for phased in structure-based approach to designing control in future electric energy systems as discussed in Section VII. In Section VIII the key question is addressed regarding how distributed control for electric energy systems could be designed for guaranteed perfomance using rigorous systems control methods. Here, again, the structure-based modeling approach is used to propose that it would be indeed possible to control the interaction variables in a distributed way by the smart balancing authorities (SBAs). An ACE-like dynamic interaction variable can be controlled by each SBA and the system would meet system-level dynamic performance as long as these entities meet the distributed control requirements. This approach is fundamental for provable plug-and-play standards for dynamics proposed in this paper. However, examples are given which illustrate that an entirely decentralized control design leads to sub-optimal control and requires much more costly control. Depending on the dynamic phenomena controlled, the cost is measured in terms of control limits required, and/or in terms of wear-and-tear of equipment. It is suggested that there exist major benefits from minimal coordinated control over multi-temporal, multi-spatial and multi-physics phenomena. At the same time, the proposed structure-based approach leads to minimal coordination of interaction variables only, and not of all states. This implementation is feasible using synchrophasors.

In Section IX we propose three possible paths toward systematic standards for system dynamics. We provide some examples of all three proposed approaches. We use the structure-based modeling reviewed in Section V as the key modeling approach for proposing and assessing alternative approaches to standards for dynamics which would ensure well-defined performance. Notably, using well-defined modeling and taking a systems control point of view at the standards design problem, it becomes possible to define standards for provable performance. These possible ways forward are discussed in light of regulatory complexity required for their implementation. They are also discussed in light of their role in supporting the evolution of today's electric power grids into smart grids capable of enabling sustainable utilization of the existing resources and the integration of new resources. We raise open questions concerning a possibility of having very simple standards similar to those in Internet and digital electronics. We suggest that it just might be possible to arrive at such standards; if this is done, this would lead to massive industry innovation. Fundamental issues which require deep research by multi-disciplinary teams of experts are described.

In Section X we conclude by emphasizing that perhaps there is no easy way out of having to rethink the power industry standards currently used. Possible avenues are fundamentally affected by what will ultimately be considered as reliable service. The central generation and high-voltage transmission planning for ensuring that the worst-case $(N-1)$ reliability standard is met at the bulk power transmission system (BPTS) level must be considered in coordination with the lower-level standards and protocols which must be designed for the new distributed energy resources. As of now, the industry has very little guidance for integrating distributed energy resources (DERs) which are not negligible in size, or for integrating huge number of very small DERs with a similar capacity of a mid-size DER, so that this is done in coordination with BPTS reliability planning and operations. This white paper offers possible approaches to defining standards and protocols in support of future coordinated service provision.

II. Summary of Standardization Efforts for Smart Grids

Unlike in some other complex man-made systems, such as Internet or electronics systems of chips, for which introduction of standards was done at the system design stage, there is no opportunity to rethink the design of standards and architecture prior to building the electric power systems. Instead, the electric power systems of today already have a well-defined physical structure and are operated according to best practices, and the design of future standards must evolve around the existing best practices.

The challenge is to introduce standards which would support evolution of future architectures, both physical and cyber. Somewhat separable challenge is the problem of standards design for future micro grids and for electric energy systems in the developing countries. This paper does not directly consider design of standards for such new systems. The emphasis is, instead, on identifying what might be possible issues with dynamics as unconventional technologies are integrated into the existing T&D large-scale electric power grids, and how to design standards for dynamics which support system evolution without experiencing near real-time operating problems.

The main issue in introducing standards for dynamics is whether it would be possible to design easy-to-use standards which would enable integration of new generation, T&D and demand technologies in a plug-and-play way without creating operating problems. At present there is much work under way which is pointing in the direction of distributed decision making for balancing predictable supply and demand in a distributed way. Knowledge is being acquired on how sub-optimal this process might be relative to fully centralized economic dispatch and unit commitment by the system operators. It is becoming evident that coordinated resource scheduling over the broad ranges of system conditions remains necessary for ensuring that power schedules are deliverable across vast nonlinear electric power grid. Independent from how is the scheduling of power done, it is essential to have fast automation in place which would ensure safe, stable and acceptable quality of service in between the dispatch intervals to manage hard-to-predict deviations of power generation, demand and transfers from their schedules. Standards for dynamics are needed to support this automation. Dynamics of electric power systems is too complex for designing its standards by stakeholders voting on standards they like. Instead, a computer-aided approach to adaptive regulation in support of integrating new technologies is needed. Stakeholders need to be presented with a verifiable approach to interconnection requirements. If a systematic method for efficient setting of well-justified requirement is in place, this would make the time and cost of deploying these technologies much less demanding.

Historically, standards in electric energy industry have primarily been concerned with meeting safety of components, power plants, load components, transmission and distribution lines, transformers, etc. The IEEE and IEC standards for safety are many and have played key role in designing protection in the electric power systems.

When efforts for deploying distributed energy resources (DERs) begun, it became important to introduce interconnection standards for these new components. A recent study provides a summary of these standards in Massachusetts, [4]. The deployment of very small resources which have no significant effects on network reliability is straightforward. However, standards for either medium-size DERs and/or a very large number of small DERs are required for systematic deployment of these resources when their effects on system performance become non-negligible. These are at the infancy stage. However, they are needed if more reliance on DERs is to be introduced [5].

Important for the discussion in this paper is to differentiate between standards at the component level, at the control area level and at the level of the system as a whole. While most of the standards were initially established for safety at the component level, standards for systems safety were developed as per needed basis. To pursue radical innovations, such as the one of digital grids [6] it is important to understand the inter-dependence of component-level specifications and system-level performance. This is fundamentally simpler to pursue in systems with little dynamics and primarily stationary changes. Revolutionary standards in digital electronics were introduced under such assumption first [7]. The need for more dynamic standards for analog-to-digital conversion (ADC) by means of highly responsive sensing and signal processing has been recognized recently and the electronics industry is working toward such standards [8].

This white paper concerns specifically possible standards for dynamics. There have been recent proposals for all DC micro grids, and even all digital power grids [9], [6]. Standards for such power grids equipped with power-electronics switching to enable DC power transfers need to be introduced. The principles for these standards may be different than the principles for standards needed to ensure no dynamic problems in bulk power transmission systems. As the penetration of low- and medium-voltage DC power grids increases it becomes critical to have standards and/or protocols for coordinating dynamic performance within an overall complex power system.

This paper recognizes that it is necessary to design a systematic framework for standardization in future electric energy systems. Given the overall complexity of today's physical electric energy systems, it is suggested that information technology (IT) and automation could play a key role in having such system in place. However, computer methods and automation in today's electric energy industry are generally viewed as having second-order effects on quality and cost of electricity service. Investment planning and operations are targeted to building sufficient capacity to ensure long-term adequacy for the forecast system demand, and to, at the same time, serve customers reliably and securely, without affecting users even during the worst-case forced equipment outages. Assuming accurate system demand forecast, and typical economies of scale supporting central large power plants investments and large-scale transmission and distribution (T&D) infrastructure to reduce long-term cost, it is easy to understand lack of perceived interest in automation; the main value of IT and automation comes from providing flexible, just-in-time (JIT) adaptation to the changing system conditions, and, also from enabling economies of scope values from multiple usage of the same hardware. The industry is risk-averse and will build more and have a bit larger operating reserve just in case conditions are not as anticipated, instead of relying on JIT and multiple use of the same equipment.

Perhaps an additional reason for the electric power industry not having relied on automation extensively in the past is the complexity of its design for guaranteed performance. It is hard for power engineers to trust automation and not have direct control of their assets in an environment in which synchronized monitoring is not in place, manufacturers' data is hard to test and the physical laws governing complex geographically vast interconnected power networks generally lead to un-tractable, non-closed form models. At the same time, the very complexity of forecasting system demand and scheduling generation so that power can be delivered to the right, often distant, geographical locations and at the right time to maintain synchronism, has led to gradually increased use of computer software and automation in today's utilities over the past several decades. The software tools have become invaluable to system operators in control centers and planners in their daily decision making.

Reconciling this complexity of designing the right software for predictable performance, with the growing needs for software to help manage complexity of the physical system is not an easy balance to strike. Deciding what to leave to the operators and what should be automated is equally as hard, if not a harder, problem as deciding which new equipment to build and use.

The challenge of deploying the right automation has recently taken on a new importance with the efforts to make the most out of the available energy resources in sustainable ways. Moreover, there are pressures to utilize all system assets, existing and new ones, as efficiently as possible. As these efforts are being pursued, it is becoming exceedingly difficult to directly relate any technical innovation, hardware or software, to the quantifiable performance improvements. Yet, it is clear that new models, communications, sensors, computer software and automation will be needed to integrate and utilize many diverse energy resources.

One possible way forward would be to introduce standards for dynamics which will support deployment of IT and automation which will enable flexible asset utilization. Designing sufficiently simple standards with explicit objectives of supporting flexible utilization in electric energy systems is a difficult but necessary task.

A. Objectives of Standardization for Dynamics

There have been many efforts over the past several years which are targeted to establishing architectures for smart grids, see [10], [11], [12] and many others. Also, recent efforts toward common information model (CIM) have been under way by focusing on standards design for characterizing the specifications of existing and new equipment in the power grids using the PTI PSS/E model used by the industry today when running the power flow, and transient stability analyses [13]. The main objective of NIST standards of this type has been to enable deployment and integration of equipment made by different manufacturers in future electric energy systems. Not surprisingly, the CIM effectively mimics the input data used today. This goes a long way toward enabling analysis of systems as they evolve, however it is not sufficient.

The first CIM versions were targeted to support steady-state power flow analyses of systems with new equipment. More recently, there are major efforts under way to standardize the input data for transient stability analyses. The expectation is that by using CIM model analyses can be done to decide whether the new equipment can be integrated reliably and what might be possible technical problems.

This white paper complements these efforts by focusing specifically on standards for dynamics. The goal is to arrive at relatively simple standards and/or protocols which allow flexibility in technology used to meet them, and, at the same time, lead to provable and quantifiable performance and justification for such standards. To move forward to establishing such standards, it is important to have a systematic computer-aided approach for modeling, and demonstrating, at least by using simulations, that the proposed standards will meet their purpose. As the first step, we define next four basic functionalities standards for dynamics in future electric energy systems should meet.

III. Four basic functionalities of standards for electric energy systems

In this paper we generalize the objectives of standards for future electric energy systems. We propose four basic functionalities that are necessary for standards to support future electric energy systems evolution.

As expected, they are somewhat unique to the electric power systems, and are as follows:

- Standards must ensure safety of components; safety of interactions among group of components; and safety of interactions of the system as a whole.
- Standards must ensure that the electric energy system continues to function as an interconnected AC system; further considerations are required to ensure that hybrid AC/DC interconnected systems are compatible and continue to function as a single interconnected system. System standards for interconnecting microgrids, ranging from AC to all DC, to the bulk AC power system must be such that the hybrid AC/DC/AC system remains in synchronism.
- Standards must meet quality-of-service (QoS) as defined by the (groups of) system users; in particular, sustained variations in frequency and voltage deviations seen by the system users (both producers and consumers) away from nominal must be maintained within the specified thresholds.
- Standards must be sufficiently user-friendly and easy-to-understand and use. As such, they must play the role of a powerful catalyst for integrating unconventional resources, demand

response, and grid control technologies. Depending on the principles of their design, they could be standards and/or flexible, interactive, self-adapting protocols.

An important notion to keep in mind as standards are designed is that today's electric energy system is actually never at an equilibrium. System dynamics are continuously driven by changes in fundamental input drivers, such as demand variations and change of equipment status. In the future electric energy systems with many small hard-to-predict variations caused by intermittent resources and responsive demand system dynamics are going to be even more pronounced. It is, therefore, going to become important to formalize our thinking about what constitutes the dynamics in an ever changing complex power grid. Once this is understood, it is possible to assess the standards for dynamics in today's industry and to propose possible standards for future systems.

It is illustrated in this paper that how well the dynamics are managed can be determined by the type of standards in place. This dependence on the type of smart grid technologies deployed, and how are they valued is fundamental. There are several possible ways of moving forward. The following are three qualitatively different paths toward standardization.

- First, one could have standards for dynamics in smart distribution systems and effectively unchanged transmission system operations standards.
- Second, standards for dynamics could be designed to ensure reliability of bulk power systems without much standardization at the distribution level. Both of these will bias evolution of the overall system differently.
- Third, one could have well-defined standards at both transmission and distribution levels, and, in particular, protocols for their coordination. We propose that such standards would provide the most harmonious evolution of systems as they are sufficiently general standards to accommodate use of many non-unique technologies.

Finally, we observe that future standardization for technical performance should also concern economic efficiency impacts on system performance, and on the performance of different groups of system users. The boundary between making standards for strictly technical performance, or enabling them to interactively enable enhanced efficiency is somewhat gray at present; it is, therefore, important to understand the trade offs between technical and economic performance implied by different possible standard paradigms. In what follows we consider more than one possible standardization path. We discuss their different impact on choice for differentiated energy services and long-term sustainability of services.

IV. Examples of Dynamic Problems in Today's Industry

In what follows we illustrate, by drawing on our earlier and current research, examples of system-level dynamical problems. These examples are arranged to illustrate specific problems with meeting objectives of standards for dynamics listed above.

A. Examples of issues with standards for ensuring system-level safety

Safety standards for components have always been the highest concern in the electric power industry. Many organizations and manufacturers have worked hard to establish acceptable operating specifications and standards for generation, transmission and distribution and customers equipment. Protection and relays are embedded into virtually every single component, ranging

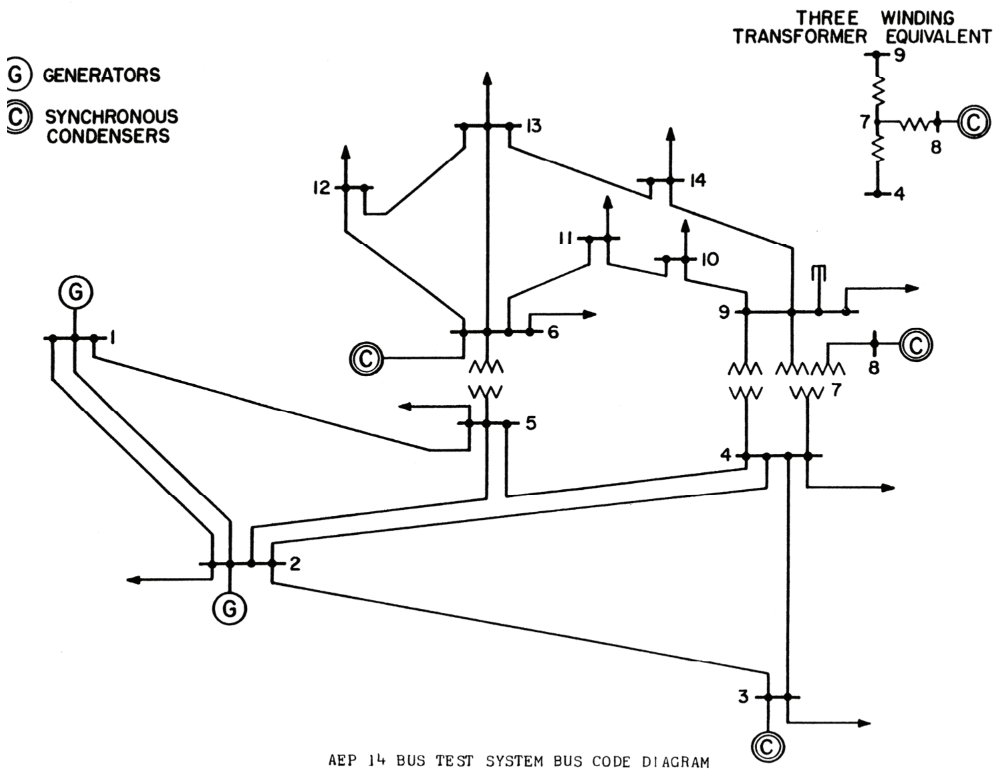

Figure 1. The IEEE 14 bus system with two sources of harmonic pollution

from the extra-high-voltage to the household appliances. However, over time, there have been dynamic system-level problems which can be thought of as being safety issues. Two such dynamic phenomena are harmonic resonance and sub-synchronous resonance [14], [15], [16], [18]. It was recently shown using simulations that harmonic resonance can occur at a system level [15]. Shown in Figure 1 is a 14-bus IEEE test system to which a nonlinear current source and/or Static Var Compensator were connected, as possible sources of harmonics.

Shown in Figure 2 is the percentage-wise distribution of the $5th$ harmonic when nonlinear current source is connected to bus number 3. It can be seen that in this case, as expected, the effects of harmonic pollution decrease with the electrical distance away from bus number 3. In other words, in this case the commonly made engineering assumption of localized system response to a disturbance holds. In this case there would be no problems with large effects of harmonic pollution elsewhere in the system. We think of this as a localized response which can be counteracted by a carefully designed local filter which cancels out locally this harmonic. Similar localized effect occurs when the source of harmonic is connected to bus number 6.

However, when harmonic source is located at bus number 8, the propagation of harmonics is system-wide as shown in Figures 3 and 4. Transfer impedance matrix is used as one measure of system-wide harmonic propagation in [15]. It can be shown that the transfer impedances are much larger when from bus number 8 to other buses, than from either buses number 3 or 6. Therefore, potential for harmonic resonance is much higher when harmonic source is located at bus number 8. Much care must be taken in practice to prevent this high propagation of harmonics; filters

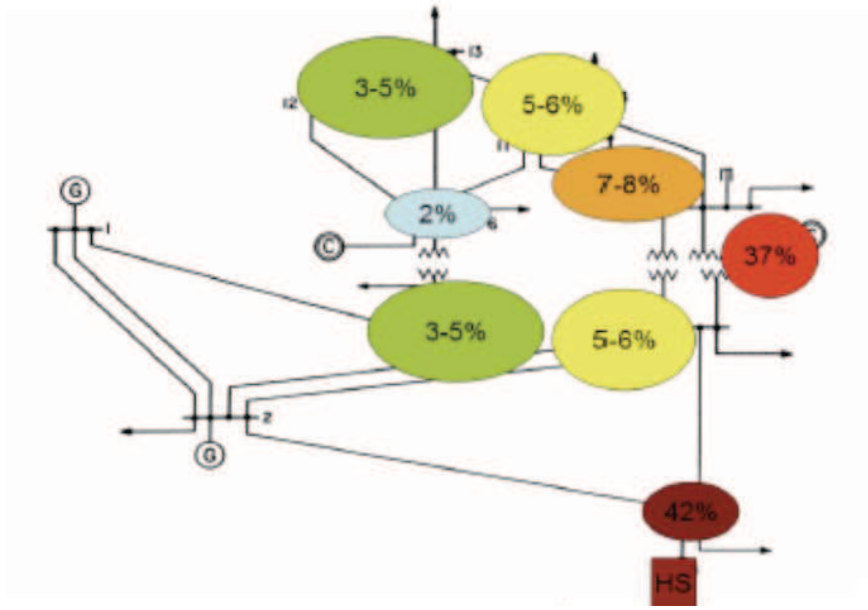

Figure 2. Localized response to harmonic pollution from bus bumber 3

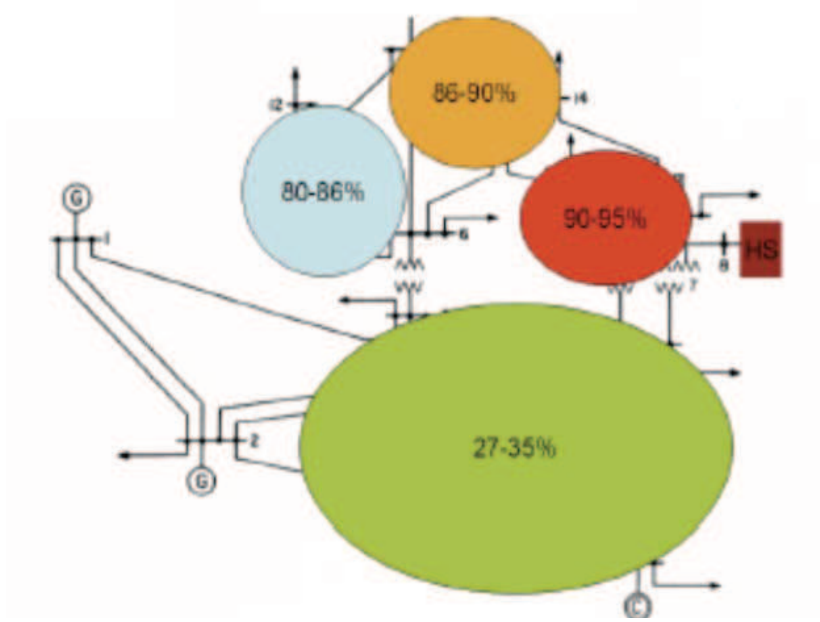

Figure 3. System-level propagation of harmonic pollution from bus number 8

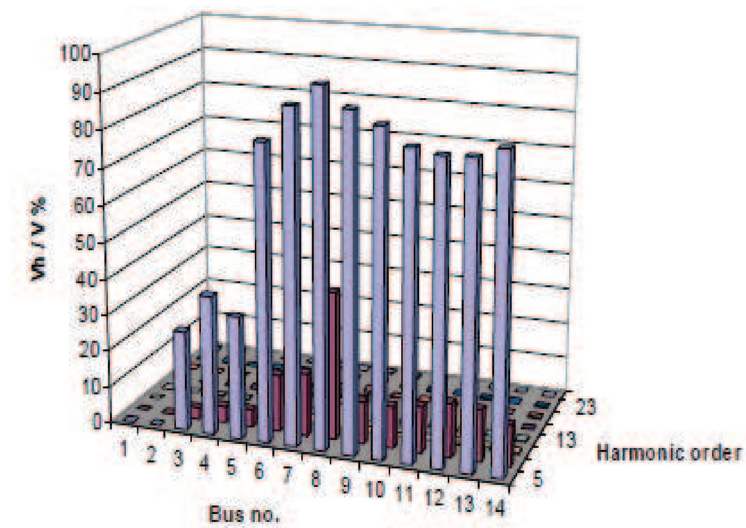

Figure 4. The percentage of harmonic voltage relative to normal voltage at different buses; source of pollution at bus number 8

need to be designed so that they cancel these propagation and reduce the effects of harmonics at the source of pollution. Otherwise, it was reported that in practice transformers can explode as a result of harmonic resonance [19]. For purposes of further discussion in this paper we observe that potential for a system-level dynamic problem, in this case harmonic resonance, is dependent on the relative location of the disturbance source. To ensure that no system-level safety problems caused by harmonic resonance occur it is important to design filters capable of canceling interactions with the rest of the system. This can be done either by placing high gain local filters, and/or by having simpler, lower-gain local filters and protocols for coordinated reduction of system-level interactions by the most effective available filters. When designing standards a decision must be made whether the problem of harmonic resonance in systems with components creating harmonic pollution should be managed locally by each component equipped by expensive adaptive filters, or by simpler local filters and minimal coordinated harmonic compensation of system-wide interactions between sources of harmonics by the dedicated higher level filters to prevent harmonic resonance problems.

A second example of potential system-level safety problems is the problem of sub-synchronous resonance [18], [16]. To start with, this is a very real problem which led to breaking rotor shafts of major turbine-generators connected to long transmission lines equipped with series capacitive compensation [18]. At present the best practice is to avoid the problem by design which avoids series compensated lines and/or has dedicated protection to disconnect the line during conditions when the SSR may occur.

There are many relevant lessons to be learned from this problem, as documented in [16]. In particular, it is essential to model the turbine-generator shaft dynamics to accurately assess whether the SSR will occur, as measured in terms of increased acceleration, and that the standard IEEE type excitation system will reach saturation during SSR. Shown in Figures 5, 6, 7 and 8

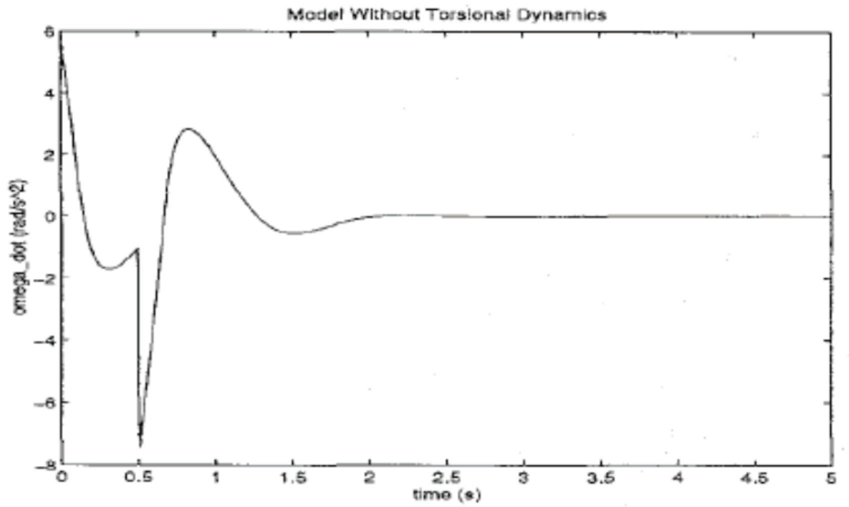

Figure 5. Acceleration of a spring-mass system without torsional shaft dynamics

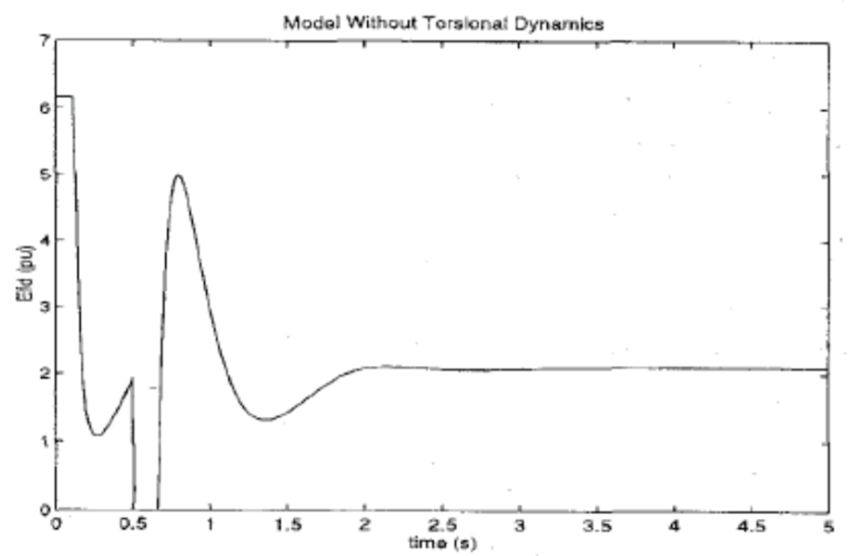

Figure 6. Field excitation of a spring-mass system without torsional shaft dynamics

are the acceleration and field excitation response during SSR without and with torsional shaft dynamics modeled [16].

This example serves as a warning that if simulation approaches are to be taken to assessing standards for dynamics sufficiently detailed models must be used. This observation brings into question potential for using model-free approaches to standard design. These must be done so that the disturbance has rich data to identify the phenomena of interest. Parameter identification becomes critical issue on the way to having good standards for dynamics. While in the past best practices have been established starting from first principles, as new technologies whose

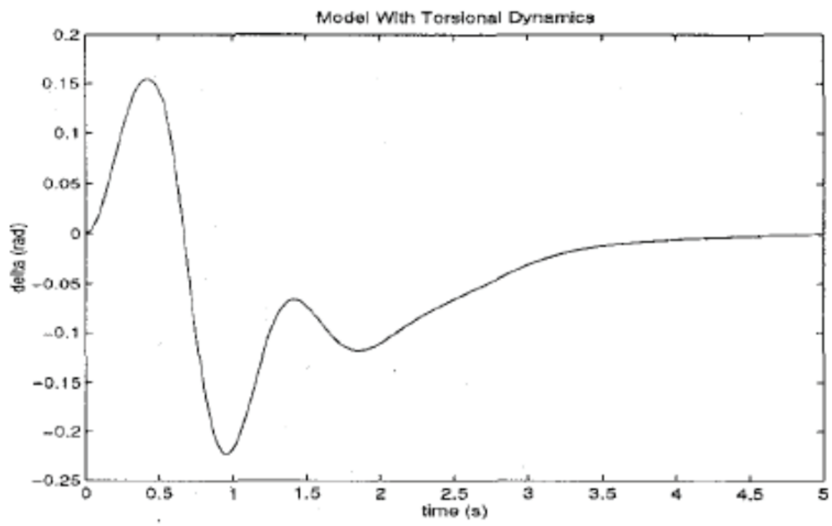

Figure 7. Acceleration of a spring-mass system with torsional shaft dynamics

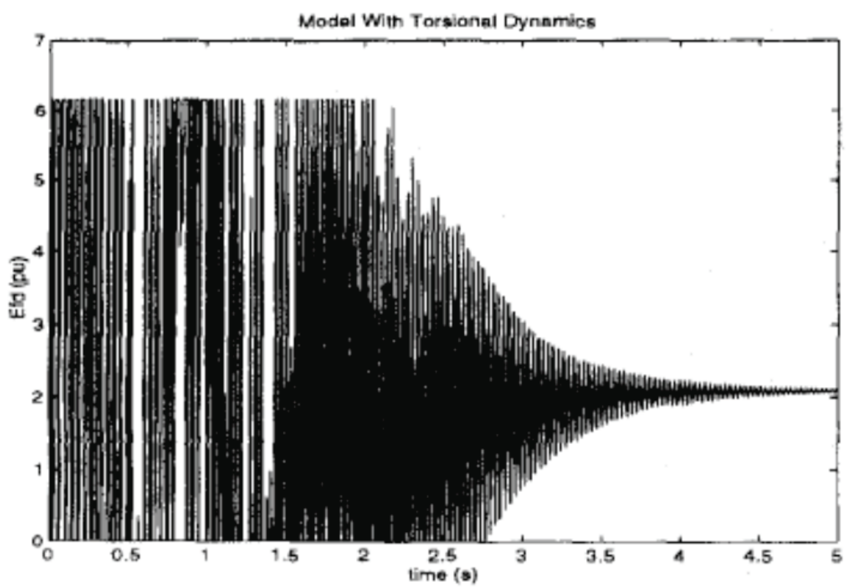

Figure 8. Field excitation of a spring-mass system with torsional shaft dynamics

models are not well known get connected to the system, it is going to be critically important to establish practices which overcome this problem by a careful combination of modeling from first principles and experimental approaches to identifying model parameters key to system-level problems like the SSR.

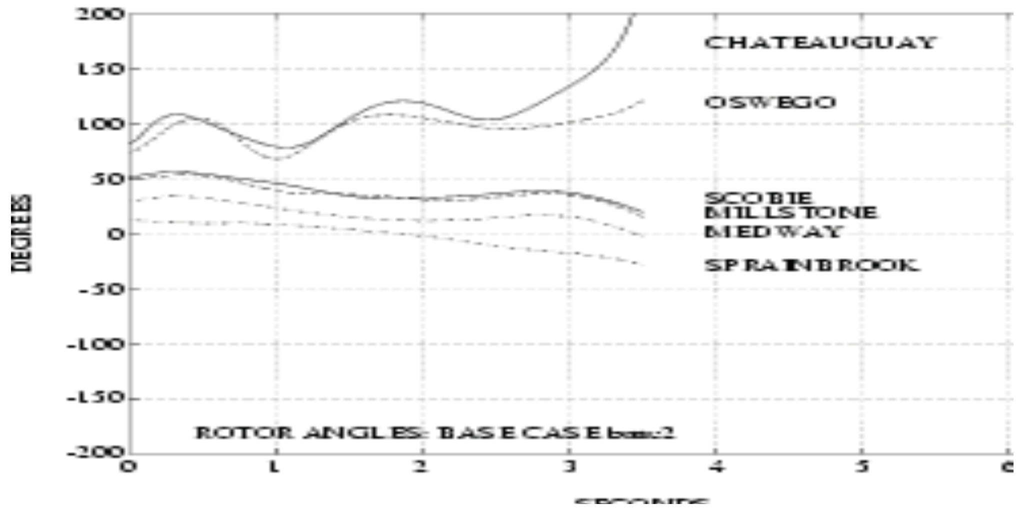

Figure 9. Loss of synchronism during a short circuit fault in NPCC [22]

B. Examples of issues with maintaining the AC system in synchronism

When attempting to design standards for ensuring that the system remains in synchronism it is important to recall that there may be many root causes of system-level loss of synchronism. The two major root causes have been in the past loss of transient instabilities triggered by large equipment failures and/or by large deviations in system load away from conditions for which the primary controllers are tuned. In the 1980's voltage collapse problem surfaced as another cause of transient instability; notably, this problem can be traced to inadequate control logic of on-load tap changing transformers, see [28] and many others. Most of the research and development work done in this area concerns analyses methods, and not control design methods [28].

As an illustration, a 38-bus 29-machine dynamic model of the equivalent NPCC system was used some time ago to demonstrate using simulations a multi-machine oscillation that occurred at 0.75 Hz, involving group of machines in New York City and the northeastern part of New York State, as well as part of Canadian power system during a five-cycle three phase short circuit of the large transmission line. The oscillation was shown to grow until a particular generator lost synchronism, followed shortly by another generator losing synchronism. This low-frequency oscillation was measured both in the real system and it was reproduced by using transient stability simulations in [22]. Shown are representative simulations in Figures 9 and 10 illustrating this loss of synchronism as seen in the collapse of angle and voltage. We note that transient stability problems can also occur during sudden changes in outputs of intermittent resources, such as wind power gusts [29].

C. Examples of intra-area system-level small-signal instabilities

For purposes of identifying what needs fixing with adequate design of standards for dynamics we illustrate here several qualitatively different types of potential small-signal instability problems. To start with, it is easy to construct examples illustrating the key need for primary

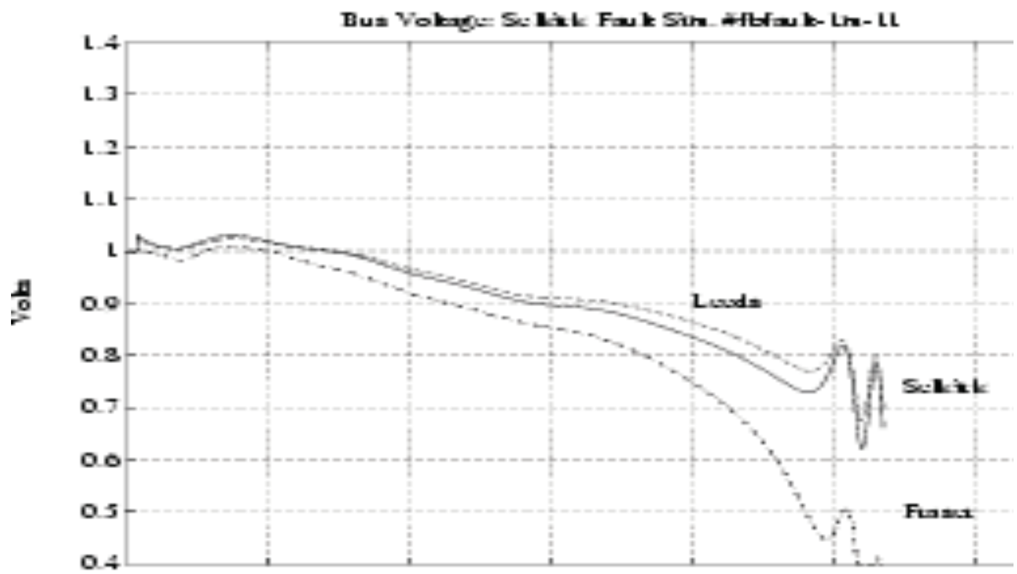

Figure 10. Voltage collapse during a short circuit fault in NPCC [22]

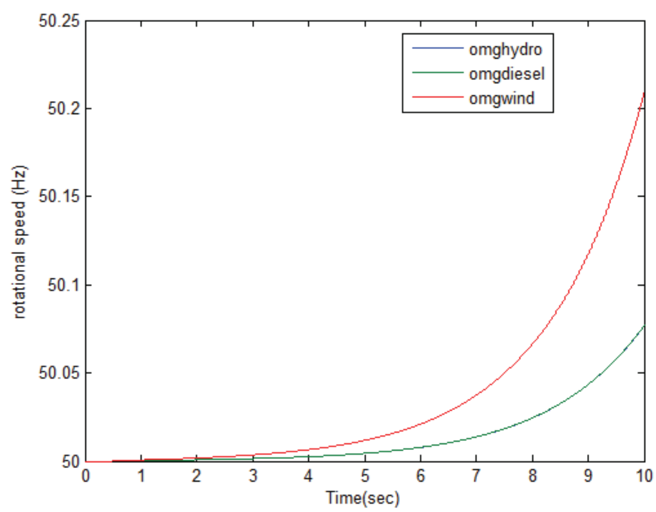

Figure 11. Flores island system without primary control [33]

control of generators, both governors and excitation systems. As an example, consider a small Flores island power grid and simulate system response without these primary controllers. Shown in Figure 11 is the unstable system frequency response without primary control. For the same system shown in Figure 12 is frequency response of the Flores island system when all primary controllers were tuned to be stable as stand-alone units but after connecting them the system-level instability occurs.

The critical role of fast excitation control on wind power plants electrically distant from the conventional power plants equipped with excitation systems is shown in Figure 13. It can be

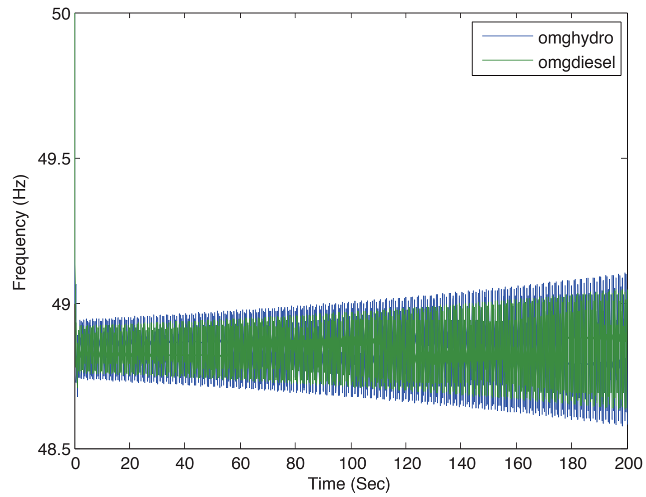

Figure 12. Flores island system with strictly decentralized governor control [33]

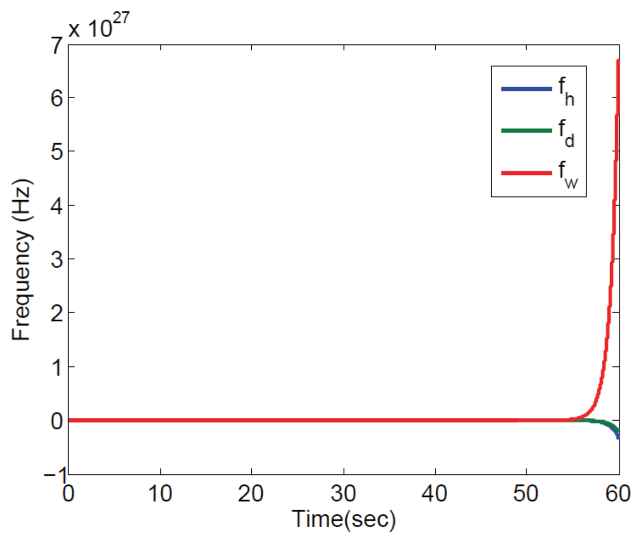

Figure 13. Wind power plant without fast voltage control in the Flores island system [33]

seen that without excitation control, or some other voltage-controlled support on wind power plant, the system frequency will destabilize.

D. Examples of inter-area system-level small-signal instabilities

Next we consider the problem of small-signal inter area oscillations, and illustrate these using the Island of San Miguel power system. Shown in Figure 14 is the interarea dynamic interaction variable when the island is organized as a two control areas system. The dynamic interaction variable of a control area represents a cumulative energy imbalance caused by the disturbances in its own area and the external disturbances created by the neighboring areas [34], [20]. A

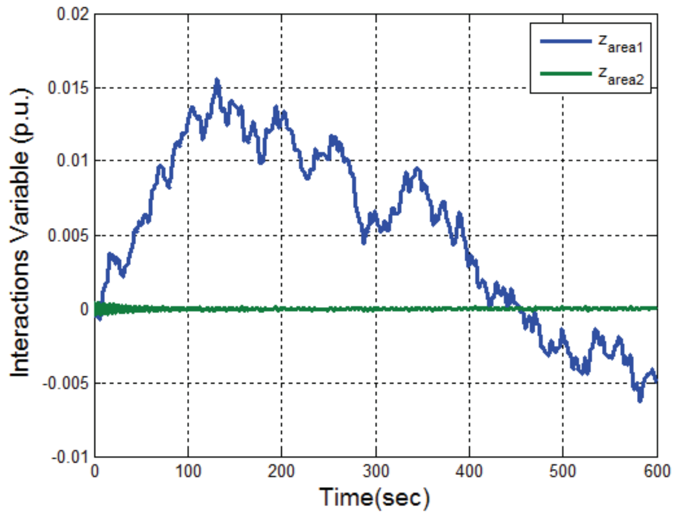

Figure 14. Inter-area oscillations caused by wind disturbances in one control area in the Island of San Miguel [33]

notion of an interaction variable is discussed in Section V later in this paper more formally. For now it suffices to think of it as a generalized area control error (ACE) when the system is dynamically changing. It can be seen that the interaction variable of area 1 is much larger than the interaction variable of control area 2. One possible setup for such dynamics of interaction variables is when there is a wind power disturbance in control area 1 and the electrical distance between the control areas is large. In this scenario the interaction variable of control area 1 simply represents the effects of wind power disturbance in that area. The interaction variable dynamics contributes to inter-area oscillations which are likely to occur as more intermittent resources are added to the system. This plot is a representative of what is likely to be seen in between control areas as more intermittent resources are added to some control areas in the continental US interconnection as well.

In addition to having inter-area oscillations caused by wind and/or other intermittent power fluctuations, intra-area frequency oscillations are likely to increase at the system locations, particularly by the power plants and other components whose inertia are small. Shown in Figure 15 are the representative frequency responses to the same wind power disturbances by the hydro- and diesel-power plants inside the control areas in San Miguel.

These examples of potential for small signal inter- and intra-area area oscillations in systems with large penetration of intermittent resources are used later in this paper as enhanced control is considered for their control. Related to standards, these are needed to support enhanced control which would prevent these oscillations from occurring.

E. Issues with quality of service (QoS)

Continuous small wind power or solar power fluctuations could cumulatively lead to unacceptable quasi-stationary deviations in frequency and/or voltage outside of pre-specified acceptable thresholds. Shown in Figure 17 is an example of frequency deviations during intra-dispatch intervals. These are result of not having sufficiently fast proportional control of governors on

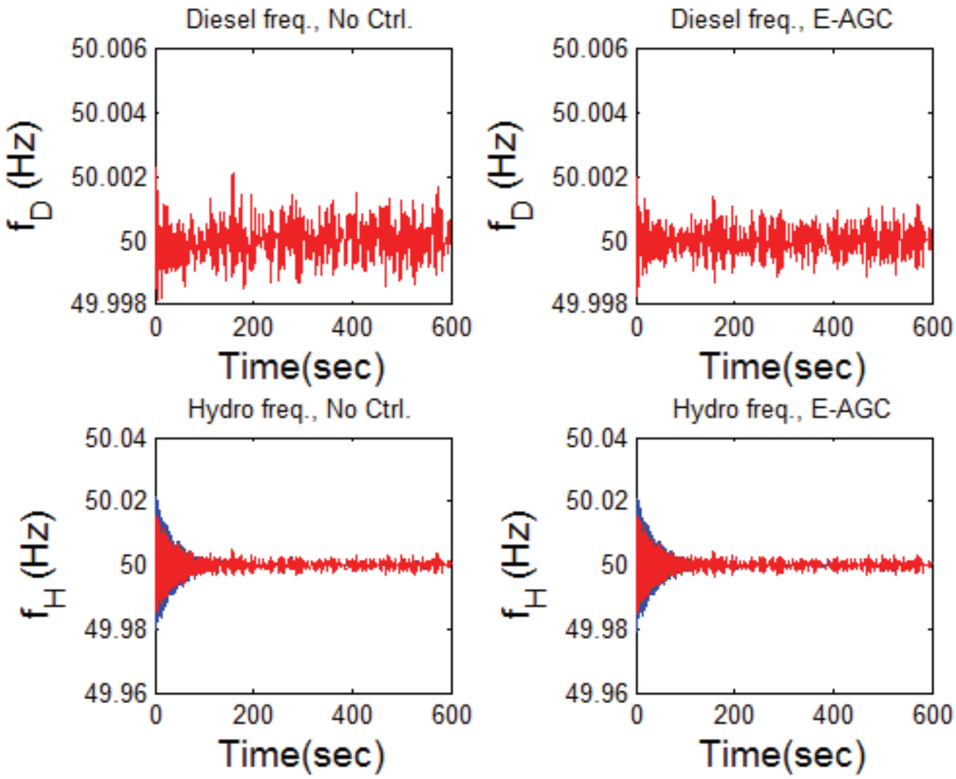

Figure 15. Intra-area dynamics with minimally coordinated inter-area oscillations control in the Island of San Miguel [33]

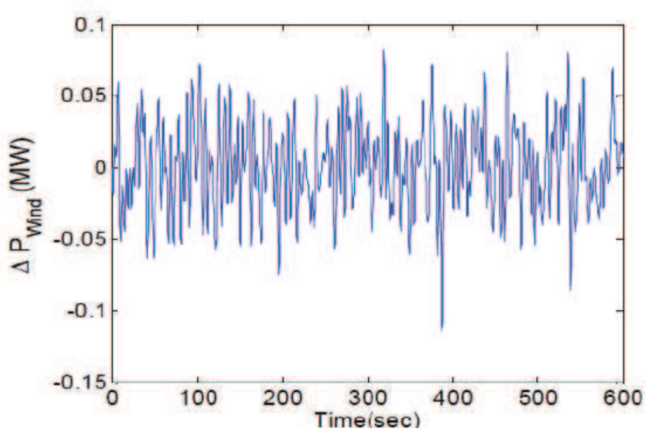

Figure 16. Wind power fluctuations [31]

some power plants in response to wind power fluctuations shown in Figure 16. On the other hand, using fast diesel power plants and/or flywheels results in acceptable frequency deviations in response to the same disturbance in the same system as shown in Figure 18.

We note here that both intra- and inter-area frequency oscillations are different at different

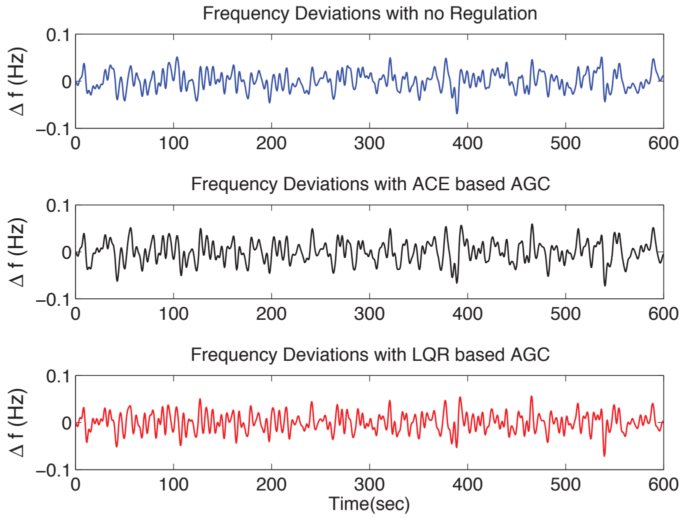

Figure 17. Poor quality of frequency in response to small wind power fluctuations [31]

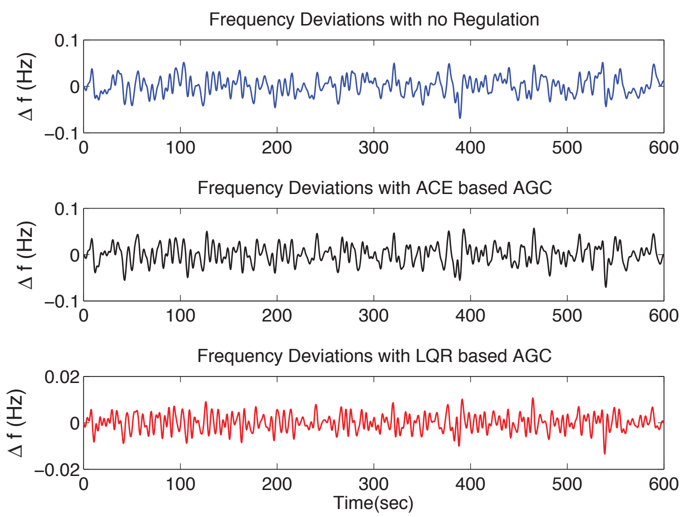

Figure 18. High quality frequency to small wind fluctuations with flywheel control [31]

locations in the system. Generally, they are function of both inertia of power plants and the electrical distances between the plants. Today's AGC models do not account for effects of electrical distances, as the ACE is measured at the control area level only. We introduce in Section V a notion of interaction variables which account for electrical distances. While in steady-state frequency is almost the same in the entire control area, this is no longer the case in systems which never settle to steady-state because of continuous persistent disturbances, as it is the case with intermittent power. This can be easily seen as frequency deviations plotted for different power plants in Figure 15, and compared to the dynamics of a single interaction variable shown in Figure 14.

Similarly, persistent small fluctuations in reactive power consumption away from forecast

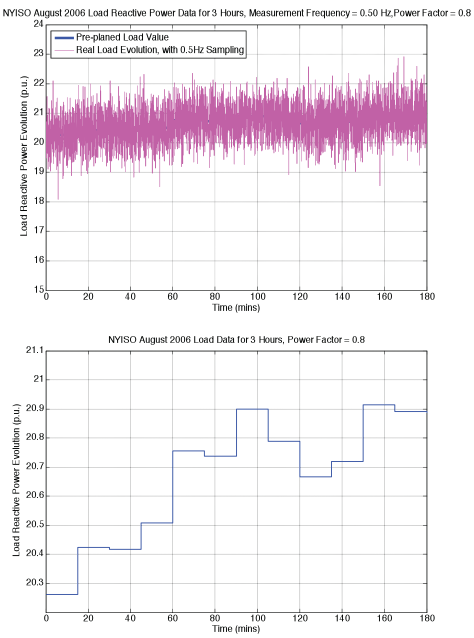

Figure 19. Forecast reactive power and small fluctuations around forecast [32]

reactive power consumption and production could result in unacceptable load voltage deviations within an intra-dispatch interval [32]. Shown in Figure 19 are scheduled reactive power and reactive power fluctuations around the schedules. The resulting wind power fluctuations are unacceptable.

F. Economic issues related to control in today's industry

Finally, it is important to stress that, in addition to possible technical dynamic problems, there exist major economic issues when it comes to enforcing acceptable system-level dynamics. Today's practice is to charge for forecast scheduling according to supply and demand laws. On the other hand, AGC and best practices for dynamics have evolved with an eye on what must be done for ensuring technical performance. The cost of control for managing system dynamics has been considered secondary to the cost of capital investments in new equipment and to the O&M cost. Most recently, standards are beginning to be enforced on governors for power plants, for example, instead of viewing these as recommended practices [36]. As the industry proceeds with these enforcements, there are many questions raised regarding the specifications set for the existing and new DER power plants, for example. As a possible solution to these issues, some time ago a proposal was made for so-called power exchange for frequency control (PXFC) [37]. In short, the idea was to require load serving entities and large industrial users to specify the bounds for their fluctuations around the forecast power, and to provide this information to the control area operator. Similarly, potential suppliers of frequency regulation would be required to provide their specifications on how they could respond to the frequency deviations (range of frequency deviations and the power output limits). It was derived in this paper that given this information it becomes possible for the system operator to decide how many units of frequency regulation to purchase in order to guarantee that control area frequency deviation remains withing the pre-specified threshold.

Resolving economic questions related to standards for dynamics one way or the other will have far reaching impacts on what gets built, and how the cost of equipment needed for regulation, load-following and stabilization gets recovered, as recognized by the policy makers. It has been well-known for quite some time that the missed opportunity cost related to AGC in today's industry is generally high [26]. As more intermittent resources are added to the system, and there is a very real possibility of having much larger deviations in power from schedules simply because any entity committed to participating in scheduling may fail to do so, the technical challenge and economics of providing ancillary services will become more pronounced. The rules for ancillary services will directly affect the standards for QoS, in particular.

To move forward, both temporal and spatial issues must be considered. Notably, in today's industry there exists a major separation between the energy and distribution management systems. When an EHV/HV energy management system (EMS) schedules generation to supply forecast system demand, only load at the substation level is estimated. This way, variations within the distribution network system, including distribution topology, distributed energy resources (DERs), and demand response, are not visible to the EMS operator. Similarly, when a distribution management system (DMS) operates the distribution network equipment and resources, it is assumed that anything connected to the substation is an ideal power source.

Lester Fink in his visionary late writing noted the trend of moving control areas closer to the end users [23]. Similar observations were made by John Zaborszky in [3]. These early contributions proposed solutions that require closer coordination of (groups of) system components within a larger control area. The most basic example of the need for such coordination is the need for coordinating control specifications between the high-voltage energy management systems (EMSs) and many medium- and low-voltage level distribution management systems (DMSs) within each control area. The need for this is higher as the deviations of power consumed by the distribution network systems are becoming larger due to high presence of DERs. Knowing the net effects of disturbances created by the distribution system users as a control area EMS is planning for regulation reserve, for example, could contribute significantly to both better technical response and more economic utilization of regulation reserves. It is very difficult to justify the deployment of very fast storage, such as flywheels, batteries, electric vehicles (EVs) and power-electronically controlled T&D equipment, for purposes of ensuring acceptable dynamic system response without having information about what is needed and how it is going to be paid for.

Ilic and Liu introduced a notion of nested control areas some time ago [2], namely control areas within which portfolia (groups of producers and consumers) are balancing their power. An early US Department of Energy M.I.T Report was devoted to rethinking control of the changing electric power industry [17]. As part of preparing this report, much input and discussion was provided by both NERC and the leading engineers whose specialty was AGC. Two types of mathematical models, one in terms of frequency and one in terms of power, were introduced and reported in that early literature. We draw on these models next in light of today's needs and build on this knowledge.

All this early work recognizes the need for tighter technical and economic specifications of technologies capable of participating in system-level control and specifications of those system users and entities that create needs for control. Using systems control language, entities creating deviations provide specifications on the ranges and types of disturbances and the suppliers specify the type and amount of control they are capable of providing. One of the proposed standards for dynamics in this paper fundamentally draws on this interactive information exchange. We next introduce one modeling approach which can be used for defining minimal information that needs to be exchanged between different entities for guaranteed dynamic performance at a system-level and for setting the principles of standards for dynamics in support of such performance.

V. A Structure-Based Approach to Modeling Complex Multi-Temporal and Multi-Spatial Dynamics in the Changing Electric Energy Systems

Today, a feed-forward ramp-rate limited economic dispatch by the EMS centers is performed routinely at the pool level, generally comprising several utilities [38].[2] AGC is performed at each control area (utility) level and it is intended for balancing slow hard-to-predict demand fluctuations. This level is referred to in the European literature as the secondary level system balancing. Finally, very fast demand fluctuations are compensated by local primary controllers, governors and AVRs, in particular.

The DMS centers are currently in forming in the US. The information about corrective actions and automation effects by the DERs will have to be accounted for as the industry begins to count on near real-time demand response. Learning customers profiles, accounting for the effects of DERs, and communicating these to the EHV/HV system operators will become the basic means for implementing both reliable and more efficient electricity services with active demand participation at value.

Today's operations and planning of regional and multi-regional interconnected electric power grids is made possible by design to simplify their overall complexity [39]. The simplifications have evolved in a bottom-up way through cooperation among different control areas.[3] The most notable is the powerful automatic generation control (AGC) scheme which is routinely used to balance supply and demand without any regional and/or interconnection-level coordination [40].

If one thinks about this, the electric power industry already has a powerful protocol for balancing supply and demand in an entirely distributed way. Much can be learned by revisiting this concept as we attempt to move forward. We propose in this section that by carefully extending this concept and relaxing implied assumptions, one can use a generalization of ACE to propose protocols and standards for future industry. In this paper we propose to do exactly this by stressing that generalizations must be pursued carefully. This requires modeling of multi-temporal and multi-spatial dynamics and related phenomena with an in-depth understanding of the underlying physics. At the end, it all pays of as it leads to a possible design of standards for dynamics which is not overly complex and it has guaranteed performance. This is a tall order.

A. *Basic structure in today's electric power interconnections*

Shown in Figure 20 is the horizontal organization of a typical electric grid interconnection. The boundaries represent control areas within the interconnection. Today's protocols for balancing

[2]Control areas have recently been re-structured and are managed by a single Independent System Operator (ISO) in areas where power is provided competitively. Conceptually, the same ramp-limited dispatch is performed as in the existing power pools, except for O&M cost functions being replaced by the bid functions of market participants selling and purchasing power.

[3]In this paper we use interchangeably terms control areas, smart balancing authorities (SBAs) and utility.

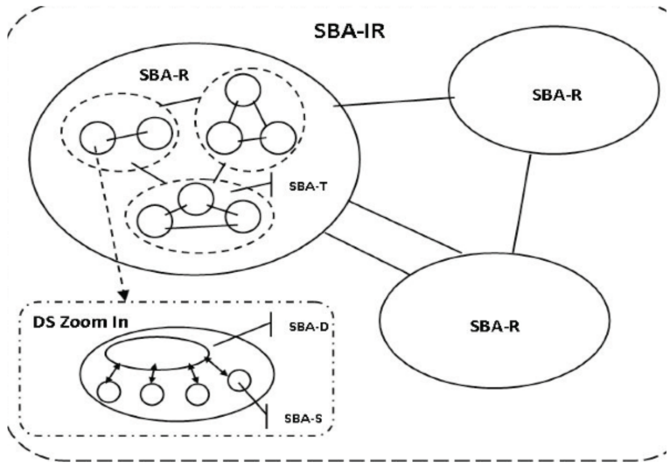

Figure 20. Interconnection-Level Structure of a Multi-Control-Area Electric Power Grid

supply and demand during normal operations is for each control area (SBA) to compensate its own ACE within each dispatch time interval. For example, the AGC protocol is for each control area to provide enough regulating power so that ACE crosses zero every ten minutes; this is the early industry standard known as the $A1$ standard [36]. After many years, defining standards for frequency regulation remains work in progress [41], [42].

It is critical to observe for what is to follow that ACE represents a linear combination of frequency deviation created by supply-demand imbalance within the control area and the net tie line flow deviation of power exchanged from the scheduled power exchange at the time of dispatch.

Each control area needs to provide sufficient regulation to bring a steady-state combination of frequency deviation and the net tie line flow deviations back to zero within each dispatch interval.

Shown in Figure 21 is a sketch of control area itself. The control area senses both the effect of internal disturbances (area-level frequency supply demand imbalance) and the effect of outside imbalances measured in terms of net tie-line power flow deviations from the neighboring control areas as a single ACE signal. This standard (protocol) is simple. It basically requires each control area to cancel out the effects of both internal disturbances and the effects of external disturbances shown in Figure 21. This is not a new observation. Siljak, in particular, has used the concept of AGC and ACE as an illustration of decentralized control design in large-scale dynamic systems [43].

B. Basic assumptions underlying today's standards for dynamics

The assumptions underlying provable performance of AGC are very strong [44], [17]. To start with, the concept is quasi-stationary, as system dynamics are assumed to be stabilizable and only a cumulative steady state error within a dispatch interval is regulated. Moreover, ACE is defined as a single scalar measure of the total control area imbalance. The contributions to ACE are not differentiated according to the electrical distances within a control area. Under these two assumptions it is straightforward to prove that if each control area regulates its own ACE, the

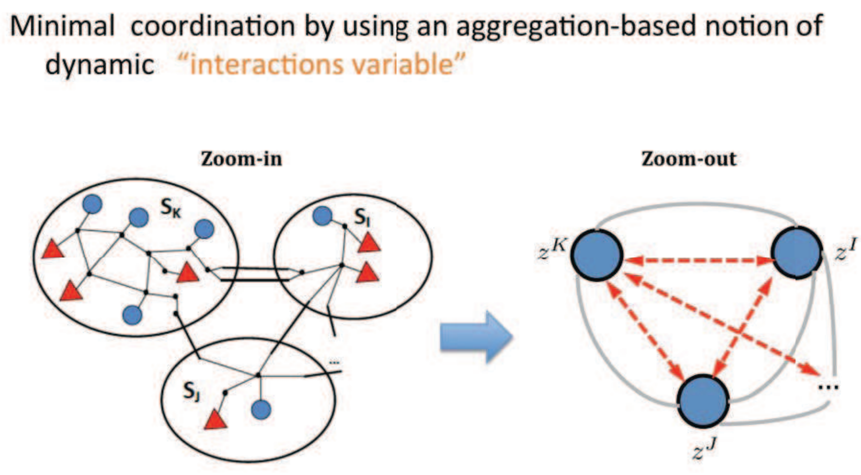

Figure 21. Control-Area (Sub-System)-Level Representation

overall system will be balanced. The gains for each control area, however, have to be carefully selected. So-called frequency control area bias b_i will have to be selected as the sum of steady state responses (droop characteristics) of the generator participating in AGC [40], [45], [2], [3].

Perhaps the most critical implied assumption is that standards for governor response, particularly the droop characteristic response of a G-T-G set, are such that the system-level dynamics is stabilized [36]. In other words, it is assumed that dynamical problems illustrated in Section IV do not occur. In what follows we revisit the validity of these assumptions and propose enhanced control and supporting standards capable of ensuring no system-level instabilities.

C. The need for enhancing governor and AGC standards

The AGC standards do not lend themselves well to eliminating transient and small-signal continuous dynamic problems described in Section IV. These problems evolve at a much faster time scale than the electromechanical imbalances controlled by AGC. As described above, they are generally caused by fast electromagnetic instabilities and/or harmonic- and sub synchronous resonance. Notably, these dynamic problems are caused by unstable interactions among different components. As such, they can not be managed by setting standards which do not account for interactions. This requires a structure-based modeling to represent the interactions between different (groups of) system components interconnected via an electric power grid. The electrical distances matter and they must be modeled, as well.

Finally, it is critical to observe that the fast continuous power fluctuations caused by intermittent power generation and responsive demand are the main reason for having to go beyond the steady-state standards for system dynamics in future electric energy systems. The transient and small-signal instability problems experienced in the past are likely to become a routine problem unless fast automation is deployed with full understanding of how to prevent these from occurring. Sudden large wind gusts will become a matter of routine operations, and will have the same effects as major losses of large equipment, unless fast automation is put in place to counteract their effects. It is with this in mind that we introduce a notion of structure-based modeling which could be used to counteract these dynamic problems without requiring excessive IT infrastructure. This structure-based model is described next.

D. Eigenmode-based and interaction variables-based modeling approach

The taxonomy of instabilities in power systems is complex [46], [3]. Standards are needed to ensure no instabilities of any type occurring. Most of the literature concerning small-signal stabilization is based on eigenmode placements-based design. Methods for transient stabilization are not fully developed primarily because of the lack of very fast sensing and communications requirements. This problem will be overcome by deploying synchrophasors, and it will ultimately become possible to close the loop by using very fast synchronized measurements. This is similar to the special protection schemes (SPSs) currently deployed at portions of the system known to have dynamical problems. The challenge is how to scale up for provable performance of the entire system. Generally, SPS is designed with specific knowledge of the problem in mind and it is not designed with full model-based understanding of system dynamics.

In addition to having fast synchronized measurements for closing the loop and implementing Wide Area Measurement Systems (WAMS)-based monitoring, much progress has been made in power electronics at medium- and high-voltage levels [9]. In particular, there is a major effort toward all DC micro grids and buildings. These all require fast power electronics switching for converting from AC to DC, and vice versa, or for controlling potential instabilities.

The major challenge concerns standards for dynamics which are not overly complex and can be deployed by the micro grids (or groups of other system users) themselves instead of putting a new burden on utilities. Questions concerning what needs to be done to manage system dynamics by the groups of users and what still must be done by the utility are key to moving forward and deploying intermittent resources, storage and responsive demand.

A structure-based modeling approach is described next as one possible approach toward standardization to ensure system-wide dynamics without having to always do full-blown system-level studies.

VI. Structure-based model for representing small signal interactions within a complex power grid

At present our understanding of the fundamental causes of potential small-signal instabilities are only rudimentary. As the dynamics of unconventional technologies is becoming intertwined with the dynamics of the existing system, the complexity of multiple time-scale responses makes it impossible to use conventional reduced order models. The dynamics of energy conversion of small resources may evolve at the rate similar to the rate of electromechanical dynamics caused by imbalances of mechanical and electrical torques on conventional power plants. The droop characteristic of new resources may be much different from the droop characteristics of conventional large-scale power plants. Some of the recent literature concerns lack of inertia as conventional power plants get replaced by intermittent resources. As a matter of fact, even the very notion of a droop characteristic in systems away from equilibria is not a well-defined term.

When it comes to designing standards for dynamics in such new systems, it becomes necessary to start with a full understanding of these complexities. The trade offs are multifold, and could be wear-and-tear of mechanically controlled existing equipment (such as G-T-G sets); and/or cost of fast-responding power electronically switched batteries and/or flywheels.

Most of analyses tools are strictly numerical, and as such are hard to relate to physical problems. Fast interactions dynamics within an electric power grid are caused by the inertial responses of its dynamic components. Today's approach to tuning controllers of generator-turbine-governor (G-T-G) sets is mainly done by representing the rest of the system as a static equivalent of the system during what may be considered to be the worst-case system outage. The basic problem with this approach is that it is hard to account for the dynamics in the rest of the system, and, therefore, it is hard to guarantee the system-level small-signal stability. Therefore, additional analyses are done for the closed-loop system dynamics to assess whether there may be resulting unstable modes. Generally no further re-tuning of G-T-G controllers is done. Instead, operating conditions are restricted so that no small signal instabilities occur. As the operating point changes, there is no guarantee that the system will remain stable.

Similarly, analyses of closed-loop of coupled electromechanical and electromagnetic dynamics (real power-voltage dynamics) are done to assess whether the system with excitation control of synchronous generators is small-signal stable. This is done for fixed controller gains (automatic voltage regulators-AVRs-, power system stabilizers-PSSs-). This inherently leads to sporadic voltage stability problems, some of which typical of cascading blackouts. It has been known for a very long time that either too-low or too-high control gain for AVRs could lead to instabilities even on a small two-node power system [25], [24]. Concordia provides an in-depth interpretation of why there exists only a range of gains for which the system dynamics are small-signal stable [25]. Unfortunately, it is very difficult to extend this reasoning to a large-scale electric power system. Consequently, as the operating conditions change, the system may become small-signal unstable unless the control gains are adjusted.

It has also been known for quite some time that the slower electromechanical interactions are result of structural singularity characteristic of any electric power system. Structurally, electromechanical dynamics of an interconnected power grid has at least one zero eigenvalue when the dynamics of all power plants is included [2], [3]. This has been the indirect main reason for introducing mathematical concepts such as slack or swing bus. These are non-physical and the only reason they are used is for mathematical necessity of avoiding structural singularity of the electric power system model. They generally make it hard to directly relate the mathematical results to the physical phenomena. The closest interpretation is the one of a swing bus being a very large generator, or a slack bus being a distributed AGC bus.

We suggest that, instead of eliminating the last generator, to avoid the singularity problems, one should keep all generators as they physically contribute to the system dynamics. The structural zero eigenvalue is useful for finding a linear combination of states in any given electric power system whose dynamics are only driven by the disturbances, internal and external. This linear combination of states is referred to as the interaction variable between each subsystem and the rest of the interconnection [2], [3], [20]. The interaction variable $z^I(t) = T^I * x_s^I$ can be shown to be a linear combination of states representing internal dynamics of the control area $x_s^I(t)$, and its dynamics are driven by the independent inputs into control area. Given a mechanical power input $P_T^I(t)$, internal disturbances $d_{int}^I(t)$ and external disturbances $d_{ext}^I(t)$, the dynamics of the interaction variable can be shown to be given as

$$\dot{z}^I(t) = T^I * A^I * P_T^I(t) + T^I * F_{int} * d_{int}^I(t) + T^I * F_{ext}^I * d_{ext}^I(t) \tag{1}$$

Matrices A^I, F_{int}^I and F_{ext}^I represent the system matrix of the internal control area dynamics, internal disturbance and external disturbance matrices. These are different for different control area topologies and line parameters. For recent mathematical treatment of this, see [20]. For purposes of introducing concepts relevant for possible design of standards for dynamics we draw in this paper a parallel between the dynamics of the interaction variable $z^I(t)$ associated with the control area I and the ACE of control area I. It follows from Equation (1) that the interaction variable $z^I(t)$ represents the total energy accumulated in the control area I as a result of mechanical power $P_T^I(t)$ and the effects of the internal disturbances $d_{int}^I(t)$ and/or external disturbances $d_{ext}^I(t)$ seen by the control area I between time $\tau = 0$ and time $\tau = t$. The quasi-stationary conditions and no electrical distances within the control area assumptions are fully relaxed and $z^I(t)$ can be used as dynamic measure of energy imbalance seen by control area I.

Depending on the phenomena which needs to be controlled, different technologies lend themselves more or less naturally to controlling accumulated energy imbalance within different time t. In what follows we use the notion of interaction variables to propose possible approaches to designing standards for dynamics which would ensure provable performance.

VII. Structure-based Modeling Approach to Designing Control in Today's Industry

In this section we return to the examples of unstable system-level dynamics in today's industry described in Section IV. To start with, it was shown some time ago that the SSR safety problem can be eliminated without saturating field excitation by replacing the existing PID controller by a feedback linearizing controller [16]. Feedback linearizing control is a nonlinear control which responds to the errors in local states of the generator and to the rate of change of current or power flows in lines directly connected to the G-T-G set. Shown in Figures 22, 23 and 24 are the rotor shaft acceleration, field excitation control and voltage phase angle deviations from the equilibrium value during the same conditions described earlier in Section IV [16]. Two important observations here are that:

- The control logic responds to the changes in interaction variable between the rest of the system and the generator; and,
- The control is nonlinear; the adaptive gain is designed so that system dynamics in closed loop is linear; it, therefore, becomes possible to design gain parameters for guaranteed performance.

Consider next transiently unstable case during the three-phase fault in the NPCC system shown in Figures 26 and 25. The same FBLC control logic used to prevent SSR is shown to be capable of preventing system dynamics from losing synchronism, all else being the same.

The same important observations can be made as for the case of SSR dynamic problem and the importance of nonlinear control canceling interaction variable between the source of disturbance and the rest of the system. More generally, FBLC can be shown to make the closed loop system behave like a set of linear decoupled oscillators, each one stabilizing itself. Control effort is needed to decouple the effects of the rest of the system on the stability of the controlled component. The concept of observation decoupled state space (ODSS) put forward by John Zaborszky and his team many years ago under the US Department of Energy funding program DE-AC01-79T29367 needs revisiting when attempting to design standards for dynamics [47], [48].

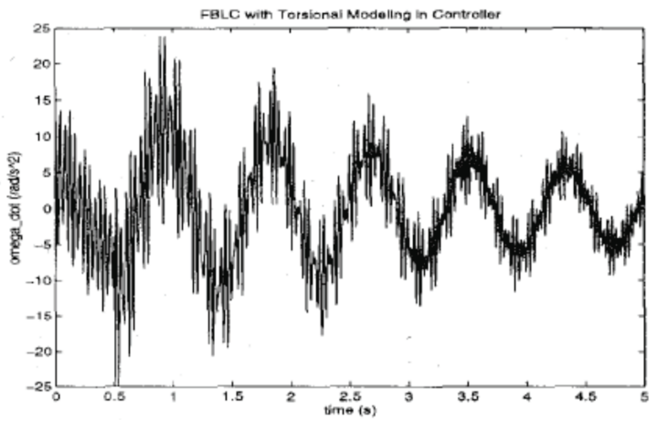

Figure 22. Rotor shaft acceleration with FBLC excitation control for preventing SSR [16]

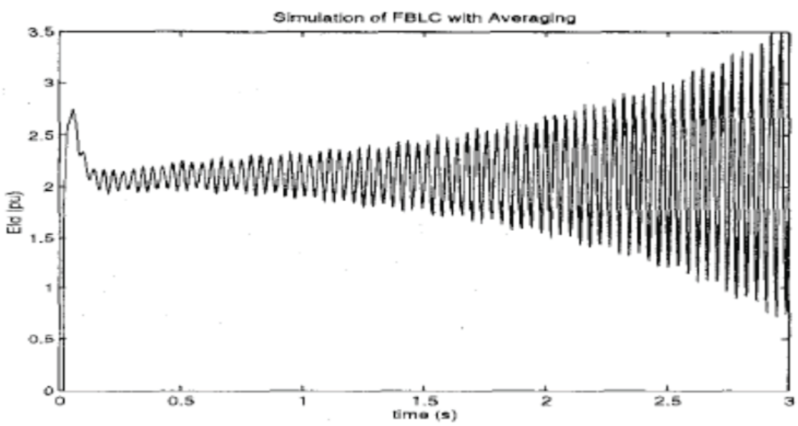

Figure 23. Field excitation control with FBLC for controlling SSR [16]

Finally, consider the problem of inter-area oscillations shown in Figure 14. It was recently demonstrated that a coordinated LQR control of interaction variables in a multi-control area interconnection can be used to stabilize the interaction variables caused by internal disturbances in individual control areas [20]. Shown in Figure 27 is the controlled interaction variable by minimally coordinated LQR [33].

The cost of coordinated LQR control of interaction variables is generally much lower than when interaction variables are controlled by the decentralized control of each area canceling out the effects of interactions without coordination. Recall that in this case this approach would imply that the control area with wind disturbances and no hydro power would have to invest in expensive storage in order to meet ACE-like dynamic standards. Shown in Figure 15 is control cost comparison of two possible control approaches, both of which capable of ensuring system-

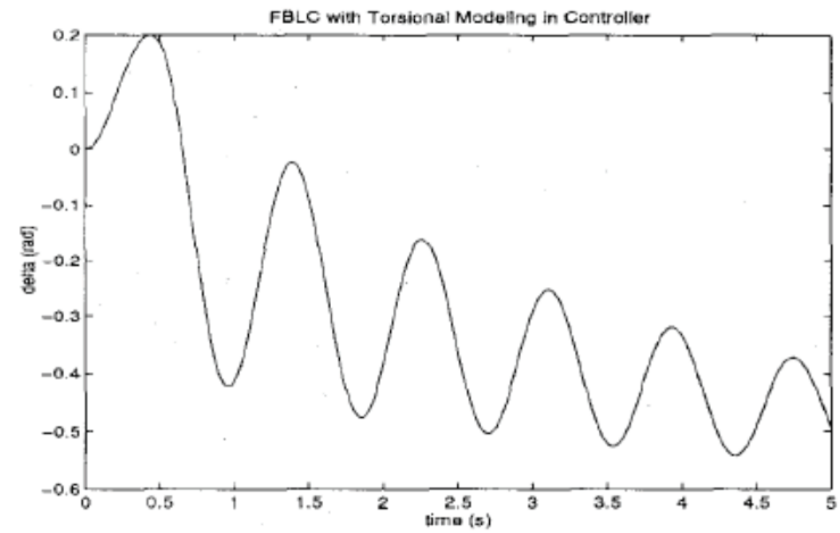

Figure 24. Rotor angle response with FBLC for controlling SSR [16]

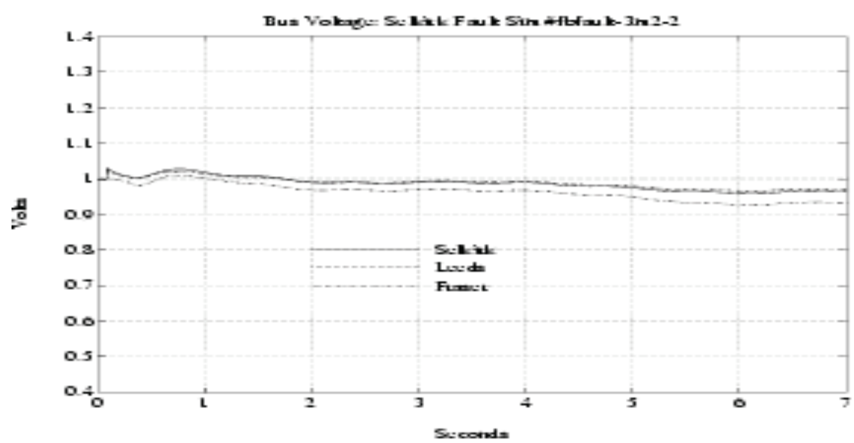

Figure 25. Generator voltage response with FBLC for preventing loss of synchronism and voltage collapse [16]

level stability and no inter-area oscillations. [4]

The above examples provide much food for further research and development. It is indeed possible to stabilize system level dynamics by all (groups of) components deploying enhanced decentralized control which cancels out the effects of interactions. Clearly, this is a more costly solution measured in terms of control effort required, but it is simpler to implement than the minimally coordinated control of interaction variables at the system level, and distributed stabilization of the (group of) components dynamics treating the effects of the rest of the

[4]The idea of dynamic regulation in today's industry recognizes potential economic benefits from minimal coordination of interaction variables between two or more control areas. Effectively, dynamic regulation amounts to treating the two control areas as a single control area.

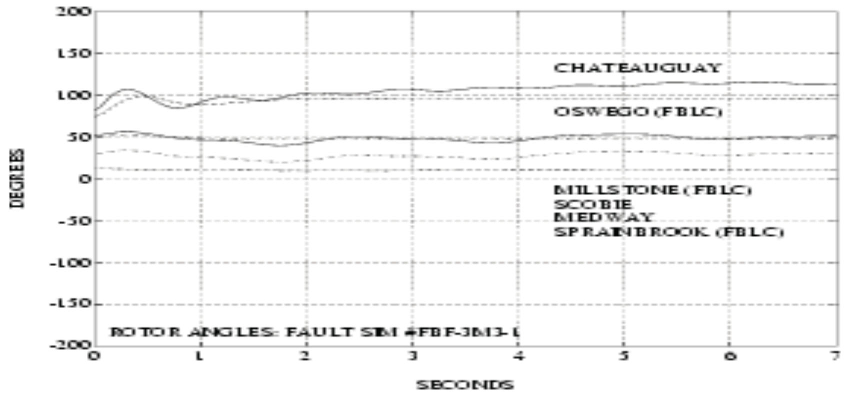

Figure 26. Rotor angle response with FBLC for preventing loss of synchronism and voltage collapse [16]

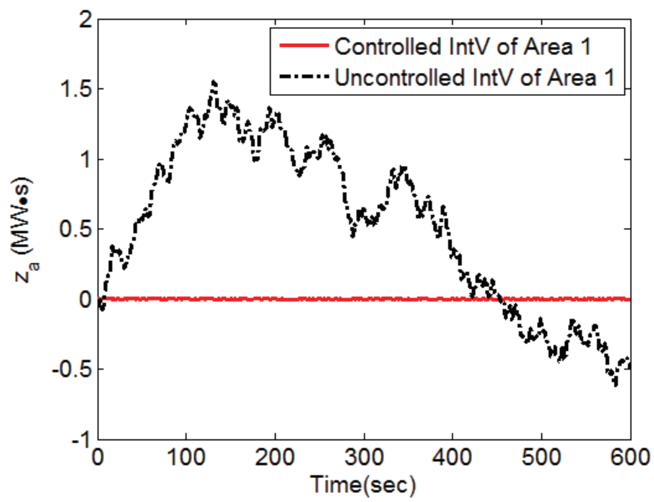

Figure 27. LQR interaction variables-based minimal coordinated control of interaction variables in the Island of San Miguel [33]

system as disturbances. Possible control cost savings could be considered for the first time as synchrophasors are being widely deployed. Moreover, the fault-tolerant enhanced decentralized control can be automatically activated in case fast communications with the rest of the system fails.

It has been quite revealing to us as we have prepared this white paper that there exists a simple structure-based unifying approach to ensuring stabilization and regulation according to the same information exchange protocols. Only the rate at which information needs to be exchanged would vary depending on the dynamic phenomena which requires stabilization. And, notably, these structure-based concepts are direct extensions of today's best ACE-based AGC regulation practice. It is therefore, possible to enhance the existing practices by building directly on what is already in place.

VIII. Decentralized versus Coordinated Control of Inter-Area Interaction Variables in Systems with Intermittent Resources

Fundamentally, the dynamics of interaction variables can be controlled either in a coordinated way or in an entirely decentralized way. While technically both solutions are satisfactory, the cost of control needed is very different. We discuss here the fundamental role of system-level coordination. The following three examples illustrate the importance of:

- the inter-control area spatial coordination of interaction variables;
- the inter-temporal coordination of interaction variables; and,
- the inter-phenomena coordination of interaction variables.

In particular, it is suggested that coordination of two control areas with qualitatively different AGC resources will result in much lower system level regulation cost than when such coordination is not put in place. Similarly, it is suggested that significant reduction of wear-and-tear can be achieved when faster interaction variables are controlled in a coordinated way by power electronically switched equipment than when each power plant is responsible for canceling out the effects of interactions with the rest of the system without any coordination. Finally, major control cost savings are possible when interaction variables between electromechanical and electromagnetic phenomena are coordinated. As an example, it is possible to avoid the need for an expensive flywheel for frequency stabilization all together by carefully coordinating control of electromagnetic phenomena for stabilizing electromechanical oscillations. These three examples are summarized next.

A. Potential benefits from coordinating inter-area dynamics in multi-control area systems

To illustrate this, we consider a two-control area interconnected system. One control area has intermittent wind power, and no fast-responding stabilizing controllers of any kind, while the second control area has hydro power. It can be shown that a coordinated Linear Quadratic Regulator (LQR) approach to managing inter-area dynamics caused by the wind disturbances in one control area leads to a much less expensive system-level control cost, everything else being equal [33].

As expected, it can be seen that expensive control must be added to the control area 1 when no coordination is put in place.

B. Potential benefits from coordinating inter-temporal interaction variables in systems with intermittent resources

As an example, consider a simple system with persistent small wind fluctuations [31]. The wind disturbance is shown in Figure 16. The small island system has a diesel power plant and a flywheel already deployed. The question is what should be the standard for compensating fast wind fluctuations. A stand-alone standard requiring that each component compensates an ACE-like dynamic signal will inherently require considerable wear-and-tear by the G-T-G of diesel power plant. Instead, a more relaxed protocol by which fast power electronically-controlled flywheel compensates the fast imbalance for the entire area is a more complex solution as it requires communications of the fast imbalance created by the wind disturbance to the controller as well as expensive power electronics control of a flywheel. In addition, quality of frequency response with carefully designed flywheel control is much better than with the diesel power plant attempting to stabilize fast imbalances. A coordinated stabilization of the interaction variable from the wind power plant (driven by the local mechanical disturbance) is generally much better. Unfortunately, this requires synchronized communications and it is, as such, more complex. Keeping an eye on possible standards for dynamics, it is clear that a more complex standard requiring minimal coordination of interaction variables is a much better, but more complex solution.

C. Potential benefits from coordinating inter-phenomena interaction variables in systems with intermittent resources

Recall from Section IV that the excitation control is critical to ensuring no loss of synchronism during dynamically evolving conditions. Based on this, we stress that significant reduction in wear-and-tear of G-T-G equipment can be avoided by using fast control capable of stabilizing voltage. In particular, shown in Figure 27 is a plot of frequency response during the same wind power disturbance shown in Figure 16, with power electronically controlled flywheel [30]. Similar effects could be achieved by power electronically controlled static var compensators and/or with DFIG on wind power plant.

As standards for dynamics are considered, it is important to provide incentives for deploying such least wear-and-tear cost solutions to stabilizing wind power disturbances. Power electronically controlled equipment of small reactive storage devices is qualitatively different from the mechanically-switched control of G-T-G sets in large power plants. The incentives and standards in support of such solutions can only be established provided that coordination of electromechanical and electromagnetic phenomena is modeled and controlled.

Finally, shown in Figure 28 is the closed-loop AVC voltage response to hard-to-predict reactive power fluctuations shown in Figure 19 [32]. A required minimal communications for coordinated AVC is sketched in Figure 29 which would enable voltage response within acceptable reliability limits. The opportunities presented to being able to stabilize and regulate both frequency and voltage for acceptable QoS using minimal synchrophasors-based coordination of interaction variables are far reaching.

IX. Proposed Approaches to Standardization for Dynamics

Based on reviewing examples of past dynamic problems, and the proposed structure-based modeling approach to automation design presented in this white paper, we propose a set of general principles which should underly the design of standards for dynamics in the evolving electric energy systems. Standards for dynamics are necessary to support structure-based automation for preventing dynamic problems from occurring in the future.

The proposed approaches to standards for dynamics are as follows:

- Plug-and-play standards for dynamics, with no requirements for on-line communications.
- System-level standards based on minimal coordination of decentralized component-level standards.
- Interactive protocols for ensuring technical performance according to choice and at value.

These three approaches are qualitatively different with regard to the complexity of implementation and effects on efficient electricity utilization.

First, the simplest, entirely plug-and-play standards for dynamics design requires that each (group of) components has sufficient adaptation to stabilize itself and to cancel its own interaction

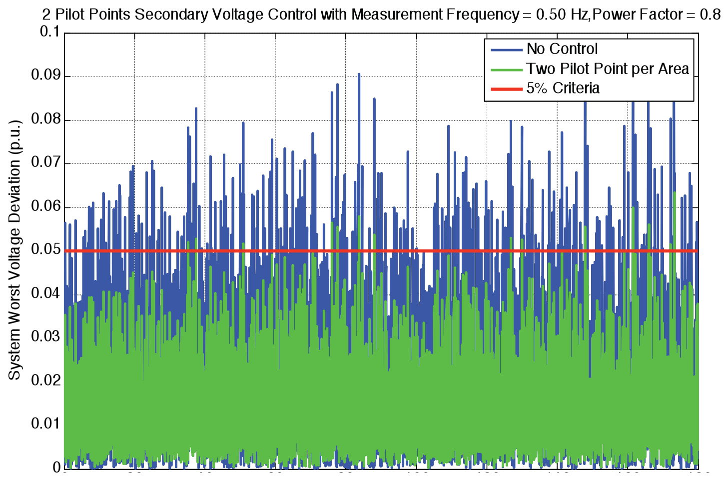

Figure 28. AVC-based closed loop voltage regulation of hard-to-predict reactive power disturbances [31]

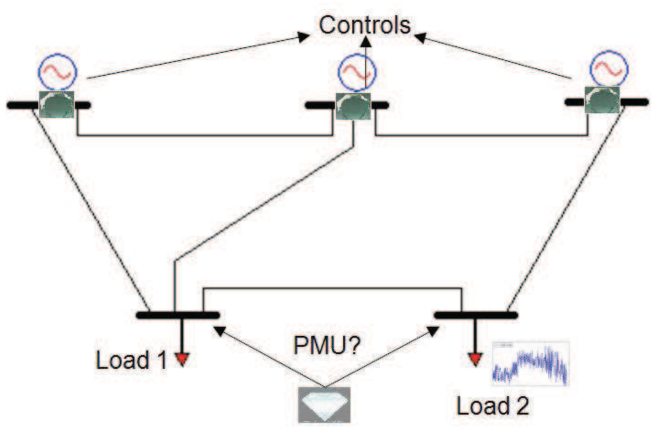

Figure 29. Synchrophasors-based minimal coordination of AVC [32]

variable with the neighboring (groups of) components. This is a simple design, yet, it is based on sufficient conditions and as such it is conservative with respect to the control requirements. Nevertheless, it can work and it can open doors to major innovation.

Second type of standards require each (group of) components to stabilize its own dynamics and to at the same time participate in minimal coordination of interaction variables managed at the higher system layer. Minimal coordination can be designed for careful management of trade off between the quality of system-level response and the cost of system-level control. This type of standards would be near-optimal, but it would require quantifiable protocol for coordination. it is illustrated in this white paper that there are major gains from such minimal coordination. With the influx of synchrophasors, the implementation of these protocols is feasible as it amounts to system-level wide area measurement systems (WAMS)-based coordination of dynamic interactions between the (groups of) components. System-dependent contributions to coordinated stabilization of interaction variables can be designed; this would ensure no inter-area oscillations. However, a potential problem with this scheme is that it is not possible to uniquely assign the responsibility to specific (groups of) components nor is it possible to provide economic incentives for participating in higher-layer dynamic coordination.

The third possible type of standards for dynamics would be a mandatory interactive participation protocol in system-level coordination by all smart balancing authorities; they would have to exchange information about their willingness to contribute to coordinated control of interaction variables at the price range offered by themselves. The SBAs not contributing to the interactive coordination of interaction variables would have to either have sufficient control themselves to cancel out the interactions with the others locally or would have to purchase control of their interaction variables from the higher level coordinator. SBAs equipped with different control technologies would provide their willingness to supply or purchase control of interaction variable dynamics at a particular price range, We refer to this framework as the dynamic monitoring and decision (DYMONDS) protocols [27]. A simple LQR method can be used to coordinate system-level interaction variables according to the least cost and within the technically acceptable dynamic performance. This way economic incentives needed to ensure system-level acceptable dynamics would be put in place.

There are many open research and development questions for all three possible pathways to standards for dynamics in future electric energy systems. Our general recommendation is to present and discuss the envisioned standards for dynamics with NERC, NIST, NASPI, IEEE and IEC and seek their comments. All these bodies should have a genuine interest and responsibilities in working toward standards for dynamics. The second recommendation is to consider an industry-academia team with a focused effort toward formalizing and adopting standards for dynamics.

Plug-and-play standards are motivated by the revolutionary success of today's standards for digital electronic systems. While these standards were introduced first for DC specifications, over time the challenge has grown when having to manage AC. Interesting analogies here are with possible plug-and-play standards for future electric energy systems. We first explain the qualitatively different challenge in implementing such massive, yet, simple standardization. We discuss the implications of such standardization for both existing power grid architectures, as well as for the evolving micro grids-type architectures. Completely decentralized plug-and-play standards are generally suboptimal without any on-line information exchange. System-level standards based on minimal coordination of technical interaction variables allow for multi-layered performance objectives at each stand-alone component level. The interactions are coordinated between the pre-specified horizontally structured subareas. In today's industry these are known as the control areas (power balancing authorities) within a large interconnected system. Standards for individual components contributing to interactions between the control areas cannot be uniquely assigned. Nevertheless, the technical specifications between the control areas are well possible.

Interactive protocols for ensuring technical performance according to choice and at value represent further generalization of interactions-based minimal coordination standards. The standards at the component level are result of distributed decision making for anticipated conditions in the higher layers, and are provided interactively to the smart balancing authority responsible for higher-level performance. The financial and technical interaction variables are multi-directional either among the components within the SBAs, and/or between the components and their SBA operator. The horizontal boundaries for aggregation are dynamic and, generally, system dependent. However, the interactions specifying both technical and financial interactions variables now uniquely define the contribution of individual components to the performance of SBAs, and SBAs uniquely define their contribution to the performance of the entire system.

X. CONCLUSIONS

In this white paper we consider a possibility of having simple standards for dynamics in future electric energy systems, similar to those in Internet and digital electronics systems of chips. Standards in these industries have been instrumental to the revolutionary innovation. The problem of designing simple standards for power system dynamics comes from the fact that a best-effort-performance is not acceptable, and this rules out direct applications of IP/TCP standards. Similarly, the dynamics in electric power systems is very complex, multi-temporal, multi-spatial and it involves multi-phenomena dependencies. This rules out the direct path of simple DC standards for digital electronics. Perhaps most notable is the problem of having to build on the legacy system, instead of designing standards for green-field systems. Finally, the organizational boundaries of today's and of the changing electric power industry make it hard to base standard design through cooperation.

Given these observations, one may prematurely conclude that coming up with simple standards for dynamics is a hopeless goal. In this paper we draw on the rich multi-temporal, multi-spatial and multi-phenomena structure in complex electric energy systems and use it a the basis for exploring effective principles for standards. The structure-based modeling approach taken rests fundamentally on representing dynamics of (group of) components within a given system in terms of the state variables defining dynamics of the components and the interaction variables defining how is the aggregate-level dynamics of each group affecting the rest of the system. This approach serves as the guiding light to stating several key objectives for dynamic standards in electric energy industry. The same modeling approach helps us identify assumptions which are currently made and which underlie several representative system-level dynamic problems in today's industry. and challenge ourselves with the question whether these problems can be eliminated in the future by more systematic automation based on well-understood standards principles for dynamics.

As a result, we propose in this white paper three qualitatively different approaches toward standardization for dynamics in electric energy systems. These can be clearly understood when assessing them using structure-based modeling approach. The simplest, plug-and-play standards for dynamic are possible. However, all groups of components must meet them and the standard amounts to requiring that each SBA stabilizes its own dynamics and the dynamic interactions with the neighboring SBAs. These plug-and-play standards for dynamics resemble today's ACE-based standard for frequency regulation. However, they have multi-temporal and multi-phenomena characteristics. The other two standards require minimal coordination and protocols for participating. These are, again, straightforward to interpret using the structure-based modeling approach to the dynamics of interest.

Throughout this paper we raise open questions concerning a possibility of having very simple standards similar to those in Internet and digital electronics. We suggest that it just might be possible to arrive at such standards; if this is done, this would lead to massive industry innovation. Fundamental issues which require deep research by multi-disciplinary teams of experts are described. Some speculative target results are discussed. We highlight that the standardization in digital electronics and consequences of having standards on huge success in technology acceptance and its use. The digital electronics standards through their simplicity have enabled a revolutionary deployment of this technology. This begs the question whether one could have equally simple standards to facilitate massive deployment of smart grid technologies. Plug-and-play solution comes the closest to it, yet it is suboptimal. The three specific mechanisms proposed in this paper are very different with respect to their ability to reconcile the trade off between having simple conservative standards and more complex standards which result in better system-level dynamic performance. The ultimate challenge will be ensuring that sensing , computing and information exchange necessary for enabling just-in-time (JIT), just-in-place (JIP) and just-in-context (JIC) adaptation is done so that the underlying physical processes are such that the envisioned standard objectives are feasible. This will require careful design of standards which recognize the fundamentals of AC power systems. The interesting opportunity is a gradual transition to a mix of AC and DC systems, and, even all DC grids at certain levels where this is economically feasible. Standards for supporting this system evolution are required. Ideally, it would be best to have standards capable of meeting technical performance at well-defined value which contributes to high efficiency of the system as a whole. seem overly complex an electric energy systems specific.

We conclude by emphasizing that perhaps there is no easy way out of having to rethink the power industry standards currently used. Possible avenues are fundamentally affected by what will ultimately be considered as reliable service. The central generation and high-voltage transmission planning for ensuring that the worst-case $(N-1)$ reliability standard is met at the bulk power transmission system (BPTS) level must be considered in coordination with the lower-level standards and protocols which must be designed for the new distributed energy resources. As of now, the industry has very little guidance for integrating distributed energy resources (DERs) which are not negligible in size, or for integrating huge number of very small DERs with a similar capacity of a mid-size DER, so that this is done in coordination with BPS reliability planning and operations. This white paper offers possible approaches to defining standards and protocols in support of future coordinated service provision.

We identify open research and development questions for all three possible pathways to standards for dynamics in future electric energy systems. Our general recommendation is to present and discuss the envisioned standards for dynamics with NERC, NIST, NASPI, IEEE and IEC and seek their comments. All these bodies should have a genuine interest and responsibilities in working toward standards for dynamics. The second recommendation is to consider an industry-academia team with a focused effort toward formalizing and adopting standards for dynamics. A focused effort is recommended as having simple standards will enable reliable and efficient utilization of the existing and newly deployed energy resources.

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