Toward Standards for Model-Based Control of Dynamic Interactions in Large Electric Power Grids

Marija D. Ilić* and Qixing Liu†
* Carnegie Mellon University, Pittsburgh, USA
E-mail: milic@ece.cmu.edu Tel/Fax: +1-412-268-9520
† Carnegie Mellon University, Pittsburgh, USA
E-mail: lqx@cmu.edu

***Abstract*—This paper is motivated by the recent needs to manage possible instabilities between electrically-connected system components and/or sub-systems (layers) in future electric energy systems. It is shown that standard state-space models of general multi-layered energy systems have fundamentally the same structure which can be expressed in terms of: 1) state variables representing stand-alone layer (sub-system) dynamics; and, 2) an interaction variable between the layer and the rest of the system. Once this is recognized, three possible structure-based control designs are derived and analyzed for their performance using a small power system model. The three control designs considered are: 1) a decentralized component (generator)-level output controller; 2) a decentralized sub-system (control area) layer output controller; and, 3) a full-state centralized system-level controller. Pros and cons of these three control architectures and their implications on three qualitatively different IT architectures and standards for dynamics in future electric energy systems are discussed.**

I. Introduction

This paper is motivated by the need for systematic control design in support of predictable dynamic performance in future electric energy systems. Today's industry practice is primarily based on off-line stability analysis for determining stable ranges of operations. Electric power system control is not designed for provably stable system-level performance. Primary control of electric power plants is typically a proportional output governor control; the local frequency deviation of power plants is considered to be the output variable of interest.

At present there are no control area-level standards for dynamics of control areas. Instead, only quasi-steady state regulation standard for automatic generation control (AGC) is in place; this standard requires that so-called area control error (ACE) which is a linear combination of power imbalances created by the internal control area disturbances and by the deviations in power exchanges from their schedules, crosses zero every 10 minute in particular. There are no standards for enforcing stable response of system dynamics at the control area layer. The system is currently not dynamically observed nor controlled. Not having formal requirements for dynamic response of power plants and control areas may lead to several operational problems, some of them not previously known or experienced.

The reasons for general lack of on-line monitoring and control are at least two-fold.

First, dynamical processes are very fast and they require robust and complex communications over far electrical distances. In the past static var compensators (SVCs) and few Flexible AC Transmission Systems (FACTS) were deployed in parts of the grid known to be unstable and, therefore, normally operated much below thermal transfer capability of the transmission system. Chester SVC in New England, Marcy SVC in New York are only two examples of such targeted installations. For purposes of this paper we observe that the SVC controllers are typically designed to respond to local measurements only. At present only sporadic wide-area measurement systems (WAMS)-based special protection schemes (SPSs) and remedial action schemes (RASs) are deployed in parts of the system particularly known to have stability problems. Only recently sensors, synchrophasors in particular, and on-line fast Global Positioning System (GPS)-synchronized communications have begun to be deployed. This has opened new possibilities to dynamically observe system state and to control relevant system outputs as conditions vary.

Second, generally hard-to-predict deviations around the forecast conditions have been small during normal conditions. This has made it possible to operate by communicating quasi-static SCADA measurements and according to the AGC regulation standards only. Potential transient stability problems, such as voltage collapse and loss of synchronism, have been generally avoided by not operating the system in ranges where large equipment failures could cause such problems. As a rule, there has been very little reliance on automated nonlinear control during equipment failures. Over the years, there have been instances of low-frequency inter-area oscillations and/or undesired interactions between different controllers within an electrically close area; notably, there exists an early documentation about tuning challenges of several types of controllers.

Most recent plans for integrating many intermittent resources and to rely on responsive demand are likely to lead to more frequent system-wide oscillations than in the past; therefore the need for more systematic design of on-line monitoring and control than in the past. The need to transfer large amounts of wind power to the load centers will enhance presence of inter-area oscillations creating "surprise" effects far away from the disturbance locations. Notably, large wind and hydro power transfers are currently limited by the potential stability problems during sudden equipment failures. This, cumulatively, leads to inefficiencies and use of more polluting resources during normal operations.

A. The IT innovation challenge

Design of a systematic IT support for predictable dynamic performance in future electric energy systems presents a major challenge to today's state-of-the-art control design of embedded cyber in complex dynamical network systems. Today's state-of-art in distributed control of complex network systems does not offer a general approach which could be directly applied to design control that ensures acceptable dynamic interactions between different components within a single control area layer, or between the control areas within the future electric energy systems. Since there is no single entity in charge of this design, this makes the problem of cyber design for smart grids a qualitatively different problem from the one of designing control for spacecrafts and airplanes, for example. Moreover, the network is spread over vast geographical areas creating major challenge to dynamic state and parameter estimation. Only recently remote fast control between a control center in particular utility (control area) and the equipment located far away in substation has begun to be installed as part of "smart grid" efforts. This, fundamentally, calls for as distributed automation as possible, with, perhaps, little requirement for coordinated fast control of interactions between the utilities.

This paper concerns basic modeling of dynamic interactions within a multi-layered future electric energy systems. In Section II an inherent structure of electric energy systems is summarized. This is followed by describing the structure-based dynamic models of these systems. The modeling approach used is intended to represent the dynamics of each layer as a function of state variables associated with the layer of interest, and the interaction variable between the layer and the rest of the system. Both physical and mathematical interpretations of an interaction variable are briefly discussed in Section III. Next, in Section IV three different control and communications architectures are considered for designing control for acceptable dynamics of interactions between the system layers. In Section V the three control approaches are simulated using a simple two-bus power system. Lessons learned are that much care must be given when moving to distributed control in future electric energy systems. Most generally, distributed control may lead to unacceptably high swings of system responses which, when prolonged, may trigger under-/over frequency protection and/or SPS/RAS malfunctioning which may disconnect other equipment and lead to an avalanche cascading effect and a wide-spread blackout. It is not clear at this point whether these scenarios are likely to occur in the actual real-world electric energy systems, it is conceptually plausible that such emerging behavior could occur. It will become critical to set thresholds for system protection with clear understanding of ranges and durations of dynamic swings, local and inter-area. Further research is needed to understand when swings are result of local disturbances and when they are caused by the far-away disturbances. Based on these findings, in Section VI three possible recently proposed paradigms for designing standards for dynamics are considered. Their pros and cons are briefly summarized. In Section VII preliminary findings, open questions and recommendations for future research are presented.

II. Electric Energy System Structure: A Multi-Layered Interconnection of Smart Balancing Authorities (SBAs)

To pose the problem of interest, consider a sketch of a multi-layered set of smart balancing authorities (SBAs) that are responsible for meeting pre-specified performance while interconnected electrically to many other SBAs (Figure 1). In future electric energy systems the SBAs could be very diverse aggregate subsystems such as microgrids, portfolia of wind power and storage, portfolia of wind power and responsive demand, or conventional load serving entities (LSEs). These SBAs are embedded within a larger electrically interconnected grid and, ideally, they should work together toward balancing system-level power imbalances according to well-defined protocols and standards which define their own responsibilities. These emerging SBAs are a generalization of today's control areas responsible for distributed balancing of their area-control errors (ACEs) and contributing to automatic generation control (AGC) for frequency regulation. A closer look into today's implementation of AGC shows that ACE is a steady-state concept and that it is based on overly simplified model of each control area which does not account for electrical distances. As such, the model can not capture truly dynamic problems such as inter-area oscillations, or going out of synchronism or voltage collapse. One way of thinking about the proposed modeling and control framework in this paper is that it is effectively a natural evolution of ACE-based modeling for AGC control which captures small signal dynamics of the electrical grid partitioned into electrically interconnected SBAs.

A. Basic structure in today's electric network interconnections

Shown in Figure 1 is a horizontal organization of a typical electric power grid interconnection. The boundaries represent control areas within the interconnection. Today's protocol for balancing supply and demand during normal operations is for each control area 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. 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.

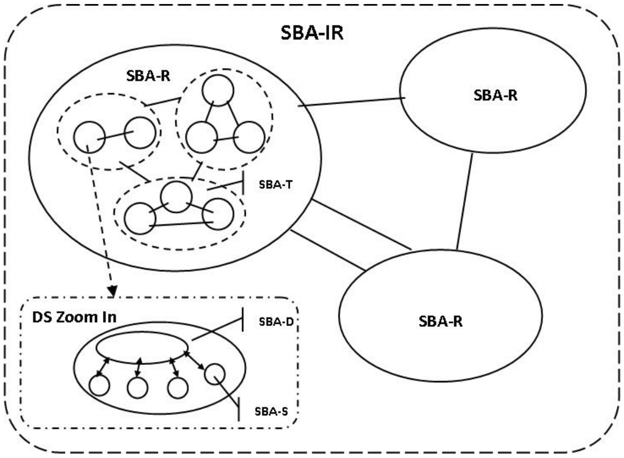

Fig. 1. A multi-layered architecture comprising Smart Balancing Authorities (SBAs)

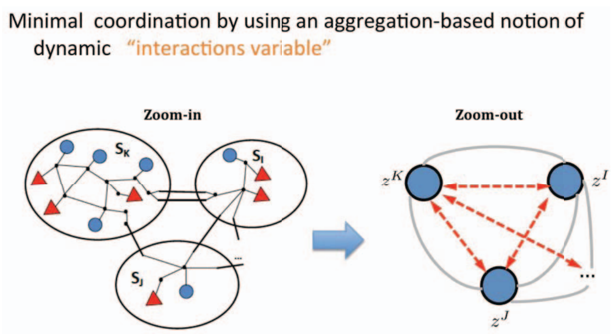

Fig. 2. Interconnection-Level Structure of a Multi-Control-Area Electric Power Grid

Shown in Figure 3 is a sketch of control area itself. The control area senses both the effect of internal disturbances (area-level frequency desupply 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 3. 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 [3].

However, the assumptions underlying provable performance of AGC are very strong. 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 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

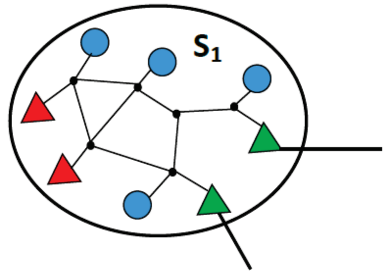

Fig. 3. Control-Area (Sub-System)-Level Representation

as the sum of steady state responses (droop characteristics) of the generator participating in AGC. Today's governor response standard for droop characteristic response is intended to ensure that system dynamics is stabilized.

III. A Multi-layered Dynamical Model of Interconnected Electric Power Systems

Drawing on the multi-layered structure of the interconnected electric power systems described above, it becomes possible to introduce a mathematical model of each layer expressed in terms of its own state variables and the variables reflecting the effects of the neighboring layers. To illustrate this we model in this section a component-layer using a synchronous generator as a typical dynamic component. We then model a sub-system (control area) layer in terms of its internal state variables and the effects of the neighboring variables. Common to both component- and sub-system layer models is that the effects of the neighboring layers can be thought of as the "interaction variables" with well-defined mathematicla and physical interpretation. This is described next.

A. Modeling of Synchronous Generators

A linearized model of a typical type of synchronous generators with its primary prime mover governor control has the following form [1]:

$$\begin{bmatrix} \Delta\dot{\delta}_G \\ \Delta\dot{f}_G \\ \Delta\dot{P}_T \\ \Delta\dot{a} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ 0 & -\frac{D}{M} & \frac{1}{M} & 0 \\ 0 & 0 & -\frac{1}{T_t} & \frac{Kt}{T_t} \\ 0 & -\frac{1}{T_g} & 0 & -\frac{r}{T_g} \end{bmatrix} \begin{bmatrix} \Delta\delta_G \\ \Delta f_G \\ \Delta P_T \\ \Delta a \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{T_g} \end{bmatrix} \Delta f_G^{ref} + \begin{bmatrix} 0 \\ -\frac{1}{M} \\ 0 \\ 0 \end{bmatrix} \Delta P_G, \quad (1)$$

where the state variables are all small perturbations around the operating point. $\Delta\delta_G$, Δf_G, ΔP_T, and Δa correspond to the deviations of generator voltage phase angle, frequency, turbine mechanical power output and the incremental change of the steam valve position, respectively. Δf_G^{ref} is the governor set-point adjustment, which will be used as the control on the secondary level. ΔP_G is the the deviation of electrical power output of the generator around the equilibrium. It couples the generator with the rest of the system. ω_0 is the rated angular velocity. M, D, T_g, and T_t denote the inertia constant of the generator, its damping coefficient and the time constants of the governor and turbine, respectively. K_t is the constant parameters of the governor-turbine primary control loop. r is defined such that $\frac{1}{r}$ represents the generator speed droop.

Expressed in terms of local state variables of the generator $x_{G,i}$ and the state variables of the components directly connected to the generator i, Equation (1 takes on the following form:

$$\dot{x}_{G,i} = A_{G,i}x_{G,i} + B_{G,i}u_{G,i} + \sum_{j=1}^{n_G} A_{ij}x_j, \tag{2}$$

where n_G is the total number of generator components. The term $\sum_{j=1}^{n_G} A_{ij}x_j$ is just $-\frac{1}{M}\Delta P_{G,i}$ in equation (1) written as a function of state variables, corresponding to the interaction between the i-th generator and the rest of the system. A_{ij} consists of at most 0s and the nonzero entries only exist when there is at least one connection between i and j. The matrices $A_{G,i}$ and $B_{G,i}$ of the type of synchronous generator model in equation (1) are written as

$$A_{G,i} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ 0 & -\frac{D_i}{M_i} & \frac{1}{M_i} & 0 \\ 0 & 0 & -\frac{1}{T_{t,i}} & \frac{K_{t,i}}{T_{t,i}} \\ 0 & -\frac{1}{T_{g,i}} & 0 & -\frac{r_i}{T_{g,i}} \end{bmatrix}, \quad B_{G,i} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{T_{g,i}} \end{bmatrix}.$$

B. Modeling of Network Constraints

When synchronous generators are interconnected via electric power grid, all the generator components should be subject to the network constraints. The network constraints are typically expressed in terms of nodal algebra equations. When modules get interconnected through a transmission network the basic Kirchhoff's laws have to be satisfied. Let $\underline{S} = \underline{P} + j\underline{Q}$ be the vector of the net complex power injections to all the buses; the algebraic complex power flow equation can be written as [1], [2]

$$\underline{S} = \mathrm{diag}(\underline{V})(Y_{bus}\underline{V})^*, \tag{3}$$

where $\mathrm{diag}(\cdot)$ stands for the diagonal matrix with each element of the vector as a diagonal element. $\underline{V}$ is the vector of all the bus voltage phasors. The kth element of $\underline{V}$ is given by $V_k e^{j\delta_{G,k}}$. Y_{bus} is the admittance matrix of the power grid.

The net real part of complex power $\underline{S}$, in general, is comprised of active power injection of the generator power $\Delta\underline{P}_G$ and consumption of the load power $\Delta\underline{P}_L$, which is $\Delta\underline{P} = \begin{bmatrix} \Delta\underline{P}_G & -\Delta\underline{P}_L \end{bmatrix}^T$. Linearizing the real part of the complex power flow equation (3) around the system equilibrium yields

$$\Delta\underline{P}_G = J_{GG}\Delta\underline{\delta}_G + J_{GL}\Delta\underline{\delta}_L, \tag{4a}$$

$$-\Delta\underline{P}_L = J_{GL}\Delta\underline{\delta}_G + J_{LL}\Delta\underline{\delta}_L, \tag{4b}$$

where

$$J_{ij} = \left.\frac{\partial \underline{P}_i}{\partial \underline{\delta}_j}\right|_{\underline{\delta}_j = \underline{\delta}_j^*}, \quad i, j \in \{G, L\}$$

is the Jacobian matrix evaluated at the system equilibrium. $\Delta\underline{\delta}_L$ stands for the phase angle deviations on the load buses. Assuming that J_{LL} is invertible in normal operating conditions, we can substitute $\Delta\underline{\delta}_L$ from (4b) to (4a) and obtain the system-level algebraic network coupling equation:

$$\Delta\underline{P}_G = K_p E \Delta\underline{x}_G + D_p \Delta\underline{P}_L, \tag{5}$$

where

$$K_p = J_{GG} - J_{GL}J_{LL}^{-1}J_{LG},$$
$$D_p = -J_{GL}J_{LL}^{-1}.$$

Matrix E is a selection matrix containing 0s and 1s such that

$$E\underline{x}_G = \Delta\underline{\delta}_G. \tag{6}$$

C. Modeling of the Interconnected System

The dynamic model of a interconnected system can be obtained by combing all its generator components, the dynamics of each of which is described by (1), and the network constraints (5) [2], [1]:

$$\underline{\dot{x}}_G = A\underline{x}_G + B\underline{u}_G \tag{7}$$

D. Modeling of the Subsystem

In real-world electric power system operation, the interconnected system, described by the model (7), is further partitioned into n_s subsystems according to geographical or institutional principles. The model of a subsystem S_i in general can be written by extracting a part of the interconnected system model, which is:

$$\underline{\dot{x}}_{s,i} = A_{s,i}\underline{x}_{s,i} + B_{s,i}\underline{u}_{s,i} + \sum_{j=1}^{n_s} A_{s,ij}\underline{x}_{s,j}, \tag{8}$$

where

$$\underline{x}_{s,i} = \begin{bmatrix} x_{G,i,1}^T & x_{G,i,2}^T & \cdots & x_{G,i,n_i}^T \end{bmatrix}^T, \tag{9}$$

$$\underline{u}_{s,i} = \begin{bmatrix} u_{G,i,1}^T & u_{G,i,2}^T & \cdots & u_{G,i,n_i}^T \end{bmatrix}^T, \tag{10}$$

are the states and control input of generators in the subsystem S_i.

IV. A Multi-Layered Control Design Control for Stabilization of the Interconnected System

A multi-layered model introduced in Section III provides a possible basis for systematic control design at different layers to ensure stable interactions between the layers. In this section, we propose a new multi-layered control approach that ensures stable response of the interconnected system. A component-layer and a subsystem-layer controllers are described next. The performance of these controllers is compared to the performance of an LQR-based centralized controller that requires full state feedback.

A. Control at a Component Layer

The goal of this approach is to embed controllers at the generator, component-layer, that ensures small-signal stability of the entire interconnected system. In the theory of weakly coupled large-scale dynamic systems, when the dynamic components are locally stabilized and the strength of the component's interaction with its neighbors are managed sufficiently small, the stability of the interconnected system can be guaranteed [3]. The proposed control approach at the component-level is inspired by this theory and assumes the component is stable by itself, which is, in specific, the $A_{G,i}$ matrix in equation (2) has no eigenvalue at the right-hand side of the complex plane.

The controller aims at minimizing the coupling term $\sum_{j=1}^{n_G} A_{ij}x_j$. We define a output variable at the component level to represent this coupling term, which is written as

$$y_i = \left[\begin{array}{llll} A_{i1} & A_{i2} & \dots A_{in} \end{array}\right] \underline{x}. \tag{11}$$

Note that matrix A_{ij} has nonzero terms only when component j is the neighboring component of i, the output variable y_i in principle aggregates the active power flows between component i and its neighbors. For the purpose of implementation, each generator component i needs a measurement of active power flows on the transmission lines connecting itself with the rest of the world or to share its measurement of state $\Delta\delta_i$ with its neighbors.

The control law is designed by using y_i as the feedback control signal for generator i expressed as

$$u_{G,i} = -k_i y_i. \tag{12}$$

The control gain k_i is obtained by solving a quadratic optimization problem

$$\underset{\underline{u}_G}{\text{minimize}}\ J = \frac{1}{2}\int_0^\infty \left(\underline{y}^T Q_y \underline{y} + \underline{u}_G{}^T R_G \underline{u}_G\right) dt, \tag{13}$$

subject to the interconnected system model (7). $Q_y \in R^{n_G \times n_G}$ and $R_G \in R^{n_G \times n_G}$ are the weight matrices for output variable $\underline{y}$ and control input $\underline{u}_G$, respectively. It is worthy noting that the optimization problem is solved at the system-level to obtain optimal control gains for each of the component. Nevertheless, the control law itself is still decentralized with information exchange only between neighboring components. The control law at component i only uses its own y_i as the feedback signal. Therefore, the control gain matrix of all the controllers $\underline{u}_G$ with respect to the output variable $\underline{y}$ is diagonal.

B. Control at a Subsystem Layer

The control at the subsystem-level to stabilize the interconnected system is designed by first introducing the concept of an *Interactions Variable* which was proposed and applied in [1], [2]. Then the Interactions Variable and its time derivative are utilized as the feedback control signals for controllers located within the subsystem.

The concept of Interactions Variable at the subsystem-level is reviewed in the following. For subsystem i modeled in Equation (8), we define the Interactions Variable

$$z_{i1} \triangleq \underline{T}_i x_{s,i},$$

which is the linear combination of the state variables of this subsystem. $\underline{T}_i$ is a normalized row vector which spans the left null space of matrix $A_{s,i}$. Note that for a subsystem when its interconnection with the rest of the system is considered as disturbance, $A_{s,i}$, corresponding to the local dynamics, will always be singular. In normal operating conditions, the degree of the rank deficiency is 1. We then combine (14) and (8) and it yields

$$\dot{z}_{i1} = \underline{T}_i B_{s,i} \underline{u}_{s,i} + \underline{T}_i \sum_{j=1}^{n_s} A_{s,ij} \underline{x}_{s,j}, \tag{14}$$

Before the control $\underline{u}_{s,i}$ is applied, the dynamics of z_{i1} is only driven by the interactions between subsystem i and its neighboring subsystems. We further define a new variable for the time derivative of z_{i1}:

$$z_{i2} \triangleq \dot{z}_{i1}.$$

The control law is designed by using z_{i1} and z_{i2} as the feedback control signals for all subsystems i, expressed as

$$u_{s,i} = -l_{i1} z_{i1} - l_{i2} z_{i2}. \tag{15}$$

The control gains of each subsystem can be tuned by solving a system-level optimization problem:

$$\underset{\underline{u}_G}{\text{minimize}}\ J = \frac{1}{2}\int_0^\infty \left(\underline{z}^T Q_z \underline{z} + \underline{u}_G{}^T R_G \underline{u}_G\right) dt, \tag{16}$$

subject to the interconnected system model (7). The weight matrix Q_z is chosen corresponding to the proper dimensions of $\underline{z}$. R_G is the same as in Section It is similar to Section IV-A that the control gains of subsystems are tuned at the system-level but the control laws are implemented locally at the subsystem-level. The control law at subsystem i only uses its own z_{i1} and z_{i2} as the feedback signal. Therefore, the control gain matrix of all the controllers $\underline{u}_G$ with respect to the output variable $\underline{z}$ is block-diagonal.

C. Control at the System Layer

In [4] The centralized control at the system-level was proposed as an Automatic Generation Control (AGC) based on Linear Optimal Control theory. Similar design approach can be applied to the small-signal stabilization. With the system-level model (7), the linear full-state feedback control law is formulate as

$$\underline{u}_G = -G_f \underline{x}_G. \tag{17}$$

The optimal control gain matrix G_f is obtained by minimizing the following quadratic cost function:

$$\underset{\underline{u}_G}{\text{minimize}}\ J = \frac{1}{2}\int_0^\infty \left(\underline{x}_G{}^T Q_z \underline{x}_G + \underline{u}_G{}^T R_G \underline{u}_G\right) dt, \tag{18}$$

subject to the system-level dynamic equation (7). Note that this control approach is both designed and implemented at the system-level. Sophisticated sensing and communication infrastructure need to be deployed for achieving the full state feedback or output feedback with full system-level observability.

V. Simulation Studies

In this section, multilayered controllers introduced in Section IV are simulated and compared using a 2-bus electric power system. The system has two synchronous generators connected through a tie-line. The parameters of the transmission system and of the two generators are listed in Table III and II, respectively. Unless specified, all the units of the parameters are in p.u.

TABLE I
Parameters of the transmission system

$\Delta\delta_{12}$	V_1	V_2	X_{12}
$\frac{\pi}{6}$	1	1	0.1

TABLE II
Parameters of the generators

Gen.	ω_0	M (sec)	D	K_t	T_t (sec)	T_g (sec)	r
1	120 π	8	0.5	500	0.2	0.25	19
2	120 π	10	0.5	300	0.18	0.23	19

Figure 4 shows the frequency response of generators 1 and 2 to the step-change disturbance when no control is applied. Slow unstable oscillations can be observed from the time response so control is necessary for stabilization of this 2-bus system.

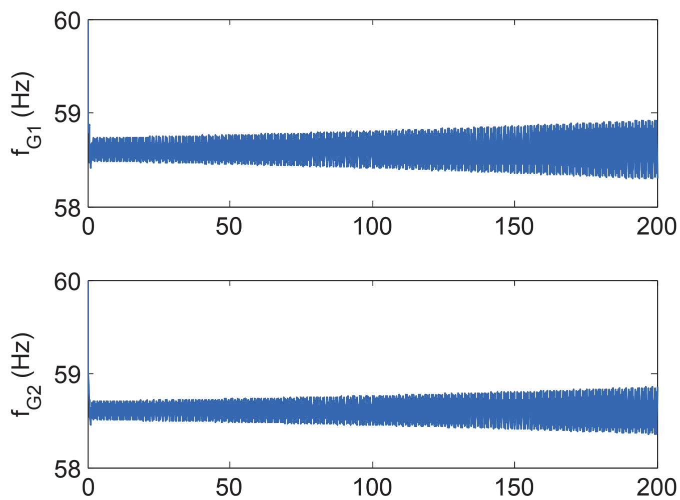

Fig. 4. Frequency Time response of the 2-bus system with no control

In Figure 5, frequency of generators being controlled are depicted. It can be seen that the controllers at both system-level and subsystem-level are able to stabilize the system and return the frequency to the original equilibrium. In comparison, the component-level decentralized control stabilizes the system but is not able to recover the original equilibrium. This is further illustrated by comparing the system's eigenvalues under different situations (in Table III). The unstable modes are stabilized by all the three control approaches; however, the zero eigenvalue, which contributes mainly to the steady-state error, is not eliminated by the component-level control. Therefore, this type of control can enhance the small-signal stability but not able to ensure the static quality of the states. Besides, in Figure 5, it can be observed that the overshoots resulted by implementing the component-level control and the subsystem-level control are much larger than by implementing the system-level control.

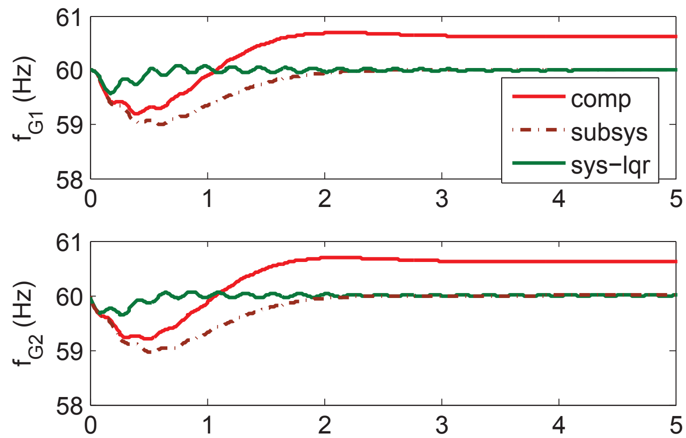

Fig. 5. Frequency time response of the 2-bus system with controllers

TABLE III
Eigenvalues of the 2-bus system under different situations

No control	Comp-level control
-82.7174	-82.8154
-76.2161	-76.5857
0.0048+27.3231i	-1.8025+27.8233i
0.0048-27.3231i	-1.8025-27.8233i
0	0
-2.5357+2.4315i	-1.7420+2.1131i
-2.5357-2.4315i	-1.7420-2.1131i
-5.2814	-2.7866
Subsys-level control	**Sys-level control**
-82.9125	-77.2083
-76.5373	-0.6205+27.2013i
-2.0337+27.9076i	-0.6205-27.2013i
-2.0337-27.9076i	-55.0634+11.2888i
-2.3452+2.2204i	-55.0634-11.2888i
-2.3452-2.2204i	-4.5274+4.6118i
-1.2963	-4.5274-4.6118i
-2.7866	-30.0129

The control inputs corresponding to the different approaches are compared in Figure 6. It is shown that the LQR-based system-level control requires much less control input than controllers at the component-level and the subsystem-level. This indicates that only sub-optimality is reached by these two types of controllers, compared to the LQR-based system-level control.

Since the main interest of this paper is regarding the small-signal stabilization, all three control approaches should be considered valid for this purpose. Special carefulness should be

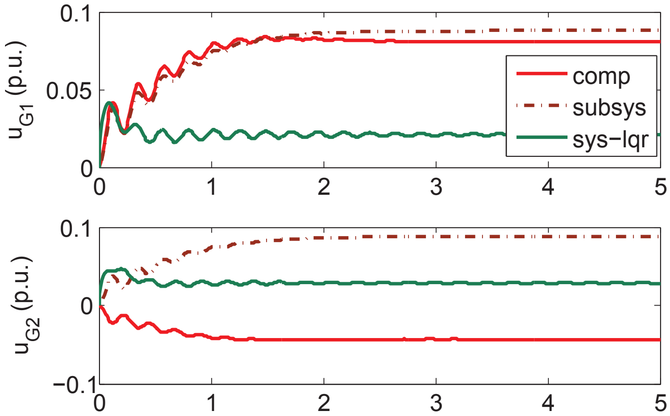

Fig. 6. Control inputs of the 2-bus System

paid, when choosing typical type of controllers, on the control cost and the infrastructures of sensing and communication.

VI. Toward Standards for Model-Based Control of Dynamic Interactions in Large-Scale Electric Power Grids

Based on assessing examples of past dynamic problems [6], and keeping in mind the proposed structure-based modeling approach to automation design presented 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:(a) Plug-and-play standards for dynamics, with no requirements for on-line communications; (b) System-level standards based on minimal coordination of decentralized component-level standards; and, (c) 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 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.

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 [5]. 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.

VII. Conclusions

In this paper we have introduced a structure-based multi-layered modeling approach for representing interactions between different layers of a complex network system and the rest of the system in standard state space form. This modeling approach sets the basis for designing distributed control capable of stabilizing interactions between different layers. The main finding is that while it is indeed possible to stabilize the interactions in a distributed way,t he quality of system response is very different depending on the type of control in place. When compared to the benchmark full-state LQR centralized control design for the entire system, the distributed controllers either require much more control and/or result in huge local swings. Standards for control of distributed controllers must be established to ensure interactions which will not trigger malfunctioning of WAMS-based protection schemes and RASs, like the one that just occurred in the recent southwest blackout. Notably, the most recent massive blackout in India was caused by the complex responses of protection to unexpected frequency and/or voltage swings.

All these events point into the need to establish standards for dynamics reflecting interactions among the layers within complex power grids of the future. Much more research is needed to design systematic control of these complex dynamic interactions within in a large power grid. Further research is needed for formalizing sufficient conditions under which a proposed multi-layered control approach will have provably stable response. Moreover, research is needed to assess trade-off between extensive communications requirements, on one hand, and more complex distributed controllers that ensure acceptable quality of system response in the power grids; it is necessary to have predictable system response that will not trigger SPS/RAS to malfunction. These difficult questions are under investigation in our group at present.

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