

# A MODELING AND CONTROL FRAMEWORK FOR OPERATING LARGE-SCALE ELECTRIC POWER SYSTEMS UNDER PRESENT AND NEWLY EVOLVING COMPETITIVE INDUSTRY STRUCTURES

MARIJA D. ILIĆ and XIAOJUN SHELL LIU

*Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA 02139*

*(Received 20 December 1994)*

This paper introduces a systematic, structure-based modeling framework for analysis and control of electric power systems for processes evolving over the mid-term and long-term time horizons. Much simpler models than the detailed dynamics specifically for control design at different hierarchical levels are obtained by applying both temporal and spatial separation. These simple models, or the aggregate models, represent the net effect of interactions among interconnected regions on specific hierarchical levels. They are exact, since no assumptions on weak interconnections among the subsystems are made. Moreover they are easily understood in terms of power flows among the regions. The approach is essential for improving present performance of the system. It is also potentially useful in a competitive utility environment in which it is critical to study the interplay between technical and economic processes.

*KEYWORDS:* Large-scale dynamical systems, hierarchical control, electric power systems, aggregate models

## 1. INTRODUCTION

Electric power systems in the United States and many other parts of the world are undergoing drastic restructuring. The trend is toward deregulating an industry which has traditionally been a regulated monopoly, and allowing for economic competition.

Much confusion arises in discussing technical and economic concepts supporting the two extremes. At one extreme, there are advocates to preserve the basic technical framework and its standards in operating the interconnected system, while accommodating competitive non-utility-owned generation. At the other extreme, there are advocates of drastic changes based entirely on economic competition. A challenging change of thinking is needed in both the engineering and economic circles to put the debates in a meaningful framework, essential for assuring that under whichever industry structure evolves, basic principles of technical operation as well as the free-market economy are met.

This is a heavy order for researchers in the area of large-scale power systems. The issues are system-theoretic in their basic nature. Researchers with the strong background in large-scale systems could identify many new theoretical challenges and develop their solutions in the context of problems directly relevant for the power industry. However, to

avoid specific formulations under technical assumptions which are often qualitatively different, one needs a systematic framework for posing these problems.

Over the years, much effort has gone into mathematical modeling of large-scale power systems and, to a lesser extent, toward systematic control designs. Given this, one would at least believe that models are available for posing the main operating problems of interest to industry at present.

Unfortunately, it turns out that some processes which are essential for relating technical operation to economics, particularly in a distributed competitive setting, have never been formulated in a systematic way for power systems. The first author of this paper strongly believes that, without such a basic framework for scientific solutions to the power systems under restructuring, not much progress can be made. Faced with this realization, we have put significant effort toward establishing a possible starting framework. The essential feature of our approach is that it naturally lends itself to the present structures, and could be used to enhance the operation of the present system. Yet, it is generalizable to any other evolving industry structure. Moreover, our approach allows for relating technical processes to economic processes and their interplay.

The material in this paper describes our framework. The paper is organized into three major parts. The first part introduces the structural modeling and control for present structures and its performance objectives. The second part describes its potential use in a distributed environment, and puts the emphasis on new technological enhancements, such as improved regional controls. The third part outlines its potential use for studying economic processes in power systems under competition, and relating them to technical processes. Even with the framework established much work remains to be done to make it useful to industry.

In the past, and at present, power-system monitoring and control has been based on a hierarchical structure under which the monitoring and control tasks are shared by different hierarchical levels. Local (primary) controllers on individual generating units are currently decentralized, in the sense that they respond to deviations of local outputs from the steady-state values, or set values, assigned from higher levels. The steady-state, set values of primary controllers are regulated at a regional level (secondary), assuming weak interconnections among the regions. The regional controllers are, however, not systematically coordinated at present, leading to deviations from optimal systemwide performance and a possibility of global system instability.

The lack of systematic coordination exists in two of the most important control problems of the power system: frequency regulation and voltage regulation. In the case of frequency control, a simple coordination scheme, commonly referred to as the Automatic Generation Control (AGC), has been automated throughout the United States, as well as in some other parts of the world. This scheme is based on a reduced information structure which allows for simple automation. Although it has been successful in practice in a relatively static operating environment, hidden problems that may lead to potential loss of global frequency regulation have been identified in the literature [1].

In the case of voltage control, a systemwide coordination level is not automated at present in this country. Instead, each administratively separate region regulates its own voltages, with interconnections to the neighboring regions neglected. However, as the system experiences unusual reactive power deficiency due to large disturbances, the need

for a systematic on-line coordination is emerging to insure the global security of the interconnected system [9]. France and Italy are the only two countries with automatic regional voltage control of electric power systems.

This paper introduces a structurally based modeling and control approach for large-scale electric power systems whose interactions among the subsystems are characterized by the interregional flows. An interconnected system is first decomposed into administratively divided regions. This natural division makes practical sense because each region has independent controls and makes its own decisions. Next, dynamics of each region are obtained by combining the local dynamics of individual generator units with algebraic power balance constraints imposed by the transmission network. Throughout this work, loads are modeled as disturbances from their expected values. Control design has the main purpose of suppressing the effects of load-demand fluctuations from normal operating conditions over the variety of time scales, ranging from seconds through hours.

Introduction of a structurally based aggregation is the second major contribution of this paper. Structural interaction variables relevant for different control levels are defined and the corresponding interaction dynamical models are obtained to account for interactions on different time scales among the interconnected regions. A particularly important feature of the interaction variables is that they are interpreted in terms of physically meaningful quantities such as interregional power flows. The preservation of physical meanings of the interaction variables, in contrast to all other aggregation methods currently known in the area of power systems, is critically important for systematic control designs aimed at responding to changes in neighboring regions. The derived aggregate models provide a basis for coordinated on-line automatic control of large-scale power systems, because they extract only information relevant for each specific control level and are of very low dimensions relative to the detailed models of typical electric power systems.

A distinct advantage offered by these results is that no assumptions with regard to the strength of interconnections are needed, in contrast to the present state-of-the-art methods which typically require the weak-interconnection assumption. Since the system is decomposed according to its structural properties, the approach is entirely independent of the strength of interconnections. Eliminating this assumption is important, because strong interconnections are needed for interregional wheelings imposed in the open-access operating mode [9].

In the last part of this paper potential use of the framework for developing concepts for competitive electric power systems is described. The basic link between economic and technical processes is described as the starting formulation for further studies.

## **2. STRUCTURAL MODELING**

This section introduces a new structurally-based modeling approach to large-scale electric power systems. While the approach recognizes the decomposition of the system into interconnected, but administratively divided regions, it does not make any a priori assumptions with respect to strength of their interconnections. The administrative regions within the interconnected system are tied together through the tie-lines, and the regional dynamics are coupled through the tie-line power flows. To maintain the traditional

decentralized control structure, an administrative region is chosen as the base for study, for which dynamical models are derived explicitly in terms of the tie-line flows. It is shown that this framework of modeling captures fundamental properties of power system dynamics and facilitates the physical understanding of the inter-area dynamics.

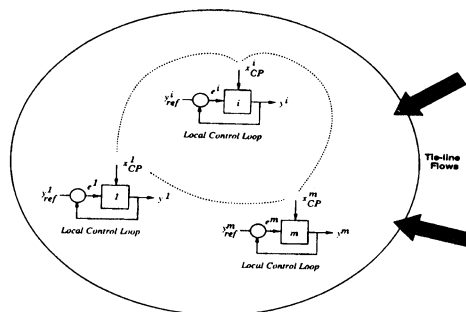
Each administrative region consists of a certain number of generating and control units, and a transmission network that interconnects these generating and control units. Typically these units are located over different locations, and each individual generator has its own local control, in the sense that the control regulates output variables associated with this particular generator only. The schematic representation of the structure is shown in Figure 1.

Dynamics of each individual unit, referred to here as the *local dynamics*, are derived in terms of local state variables of each unit. If the transmission network were not present the local dynamics of these generating units would be completely decoupled. The role of the transmission network is to constrain outputs of individual equipment by imposing power balance conditions on subset of local variables of all generators and loads connected through the transmission network. The subset of local variables directly constrained by the system interconnections is referred to as *coupling variables*. The local dynamics of individual units, in the form of ordinary differential equations (ODE), together with the algebraic constraints imposed by the transmission network, form the dynamics of each administrative region in the form of differential-algebraic equations (DAE).

It is well known that DAE problems are very difficult to study. The approach proposed here is to convert the DAE problem to an ODE problem by differentiating the network constraints under an assumption which holds for a very wide range of system operation. A standard state space nonlinear dynamical model for the administrative region in the form of unconstrained ODEs is obtained by combining local dynamics for individual units with the differentiated network constraints. The resulting dynamical model is in an extended state space, since the coupling variables also become states.

The developed structural dynamical model offers an essential, yet simple, vehicle for rigorous analysis of the power system dynamics. The model is uniquely suited for controlling inter-area dynamics at all time horizons.

The developed structural dynamical model also provides a theoretically solid basis for hierarchical control design of power systems to reject load disturbances over the



**Figure 1** An administrative region with local controls.

widespread frequency spectrum. Much simpler models than the detailed dynamics specifically for control design at different hierarchical levels are obtained by applying time scale separation techniques to the new structurally based models proposed here. These simple models, or the *aggregate models*, represent the net effect of interactions among interconnected regions on specific hierarchical levels. They are exact, since no assumptions on weak interconnections among the subsystems are made.

## 2.1. Modeling Issues

Prior to introducing this modeling process, general issues related to power system analysis and basic modeling assumptions made are reviewed such as time scales, network and load modeling, control hierarchy, and the frequency/voltage decoupling assumption.<sup>1</sup>

*2.1.1. Time scales.* Modeling and control of large-scale systems usually exploits significant time scale separation among a variety of processes. Due to these different time scales, dynamics and responses of the system exhibit different characteristics. Much of the analysis work is currently available for studying shortest response of the system to fast disturbances. Very little systematic analysis is available for system responses over the mid- and long-term time horizons. In order partly to eliminate this gap, it is adopted here that, for short-term stable operations, steady-state outputs of fast dynamics can be viewed as the moving equilibria under slower disturbances, forming a discrete event process (DEP) over longer time scale. A fundamental difference between this class of processes and the continuous dynamics is that a DEP, under certain conditions on the continuous dynamics, is driven solely by control actions and disturbances.

Electric power systems, generally large in size and complex in operation, typically display this special class of processes. The local (primary) controllers stabilize system dynamics to within a threshold of their-steady state reference values with a very fast time constant. The steady-state outputs of these primary controllers are regulated at a regional (secondary) level with a significantly longer time constant than the primary controllers, forming what can be viewed a DEP process. To fully optimize the operation of a system consisting of several electrically interconnected regions under varying loading conditions, the reference values of the output variables are adjusted at an even higher (tertiary) level with a still longer time constant than the secondary.

Most important sources of different time scales include loads which vary over different time scales and different electrical distances within a large-scale interconnected network. Power systems involve huge number of devices interconnected over far geographical and electrical distances. The connections among these devices within an administrative region (electric power utility) are relatively meshed and strong, compared with very sparse, and normally weak tie-line interconnections among different administrative regions. The meshed or strong intra-area connections represent shorter electrical distances and the sparse or weak inter-area connections imply longer electrical distances. Loads typically have widespread frequency spectrum. They are modeled as containing dynamics at three qualitatively different time scales, fast fluctuations, mid-term and long-term variations.

---

<sup>1</sup> Modeling approach developed here is generalizable to the coupled dynamics.

The controls responding at these three distinct time scales are the basis for a hierarchical control scheme to stabilize the frequency and voltage throughout the system.

As a convention throughout, we refer to the fast transient dynamics of the system as the *primary* process, with typical time constant  $T_p$ , the DEP on the mid-range time scale as the *secondary* process, with typical time constant  $T_s$ , and the slowest process as the *tertiary* process with time scale  $T_r$ . The primary process is simply the continuous dynamics of the system, the secondary process is the set value adjustment by the regional controls over mid-time horizon, and the tertiary process is associated with the slowest adjustment of system settings relevant for the entire interconnected system.

Since the secondary and tertiary processes are activated only at discrete times, any variable  $v$  of interest can be decomposed into

$$v = v(t) + v[k] + v[K], \quad k, K = 0, 1, 2, \dots \quad (1)$$

where  $v(t)$  is the continuous component associated with the primary dynamics with time scale  $T_p$ , the discrete secondary process is defined as  $v[k] = v(kT_s)$ , and  $v[K] = v(KT_r)$  is the slowest component associated with the tertiary process. A schematic presentation of relevant time horizons is illustrated in Figure 2.

*2.1.2. Network and load modeling.* In large-scale power system studies, the transmission network is modeled as a linear circuit, normally with inductances, resistances and shunt capacitances. For the frequency range of interest here, dynamics of the transmission network are neglected. Under this modeling assumption, the transmission network effectively imposes algebraic constraints to the dynamics of the local generating units and their local controls. The constraints are simply the real and reactive power balances. Generator local dynamics in the form of ODEs, together with the algebraic network constraints, lead to a constrained dynamical problem of a DAE form.

Loads are modeled as sinks or sources of real power  $P_L$  and reactive power  $Q_L$ . The deviations from constant power sinks/sources are further modeled as external disturbances to the system. Although more realistic models include dependence on their voltage and frequency, these models are not presently actively used for on-line control of the interconnected system. Using the notation introduced in (1), loads are represented by

$$P_L = P_L(t) + P_L[k] + P_L[K] \quad k, K = 0, 1, \dots \quad (2)$$

$$Q_L = Q_L(t) + Q_L[k] + Q_L[K] \quad k, K = 0, 1, \dots \quad (3)$$

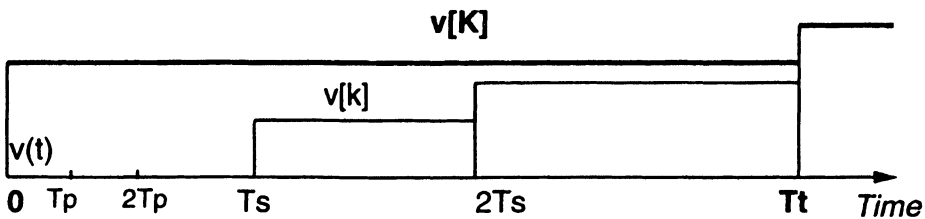


Figure 2 Multiple time scales.

for real power  $P_L$  and reactive power  $Q_L$ . In this equation,  $P_L(t)$  and  $T_p(t)$  are the fast continuous fluctuations,  $P_L[k]$  and  $P_L[K]$  represent variations over the mid-term horizon,  $Q_L[k]$  and  $Q_L[K]$  correspond to variations of the load on the long-term horizon.

## 2.2. Present Control Hierarchy

Corresponding to the three different time scales, monitoring and control of large-scale power systems typically employs a hierarchical structure:

- *Primary control*: This level is most often entirely localized in the sense that controllers respond to the local output variable changes only. The main function of primary control is to correct for small, fast output deviations caused by fast load disturbances. Excitation and governor systems are the main primary controllers responsible for voltage and frequency controls, respectively.
- *Secondary control*: This level is concerned with changes at the regional level, considering interactions with the neighboring regions to be small. Its main function is to eliminate frequency and voltage deviations at certain critical locations over the mid-term time horizons. These deviations are caused by slow load deviations. Adjusting speed-changers of governors and terminal voltages of the generators are the main control objectives at this level of hierarchy.<sup>2</sup>
- *Tertiary control*: This level is concerned with the coordination of secondary controllers by incorporating effects of interactions on the quasi-static changes of the interconnected system over the long-term time horizon. The ultimate goal of this coordination is to achieve a systemwide optimal performance over the long-term time horizon.

In terms of the load decomposition, the main purpose of the primary frequency and voltage controllers is to cancel the effects of the fast load fluctuations  $P_L(t)$  and  $Q_L(t)$ . The regional secondary controllers are designed to control frequency and voltage under the slower load changes  $P_L[k]$  and  $Q_L[k]$ . The systemwide tertiary controller is intended to update settings at secondary controllers in response to slow nominal load changes  $P_L[K]$  and  $Q_L[K]$  over the time horizon  $T_r$ .

## 2.3. Decoupling Assumption

It is well understood that, in a static operation, real-power injections to a power system closely affect voltage angle differences across the transmission lines, and that reactive power injections closely affect voltage magnitudes, under normal operating conditions. In other words, sensitivities of real powers to phase-angle differences, and sensitivities of reactive powers to voltage magnitudes are relatively larger than the cross-sensitivities of real powers to voltage magnitudes and reactive powers to phase-angle differences. This property is referred to in the power systems literature as the real power/voltage decoupling assumption.

---

<sup>2</sup>The control hierarchy is described in terms of most standard controls, that is, generator controls. Our concepts directly apply to many other controls available on modern power systems [8].

Under normal conditions, power systems operate in a quasi-steady state on slow time scales, that is, the system reaches its steady state within the fast time scale  $T_p$ . Therefore, it is generally a valid assumption that real power/angle dynamics and reactive power/voltage dynamics are decoupled in normal operating conditions. In order to exploit the most fundamental characteristics of power system dynamics, and not confuse with complex mathematical expressions associated with the coupled dynamics, the decoupling assumption of real power/frequency and reactive power/voltage dynamics will be made throughout this framework. This, however, does not imply that the decoupling assumption holds in general.

## 2.4. Modeling Process

A complete dynamical model of any power system is the combination of the local dynamics and the network coupling. This structural decomposition is schematically illustrated in Figure 1. Keeping in mind the general background of a reader, we present the material using standard systems jargon, instead of specialized power systems formulation in terms of frequency or voltage. Specific illustrations of the results can be found in [9], [10] and [11].

## 2.5. Local Dynamics

Let us define  $x_{LC}^i$  as the local states of generator  $i$ . One can express local dynamics of this generator in a general form as

$$\dot{x}_{LC}^i = f_{LC}^i(x_{LC}^i, u_{LC}^i, x_{CP}^i) \quad (4)$$

where  $u^i$  is the control input to the generator, and  $x_{CP}^i$  represents the coupling variables which relate local dynamics of different generator sets. For example, in the case of real power/frequency dynamics, the coupling variable is simply the real-power generation of the generator. Real-power generations of different generators are coupled together by the transmission network that connect different generators. The primary task of the local controller is to stabilize the local output variables of the specific generator to their desired settings, which can be calculated locally or more often given by higher level controls. Assume that

$$y^i = C^i x_{LC}^i \quad (5)$$

is the vector of output variables of interest for generator  $i$ . Let  $y_{ref}^i$  represent the desired settings for output variables. The local control  $u_{LC}^i$  is typically a feedback control designed using the error signal

$$e^i = y^i - y_{ref}^i \quad (6)$$

After appropriate design of the local controller, the closed-loop dynamics of the generator set can be written as

$$\dot{x}_{LC}^i = f_{LC}^i(x_{LC}^i, y_{ref}^i, x_{CP}^i) \quad (7)$$



We now derive local dynamical models for all generator units in the network. As discussed in the previous section, we choose any administratively divided region as the base system for our study. Consider here such a region consisting of  $m$  generator units. Define the local states, output variable settings, and coupling variables for the region as

$$x_{LC} \triangleq \begin{bmatrix} x_{LC}^1 \\ \vdots \\ x_{LC}^m \end{bmatrix}, y_{ref} \triangleq \begin{bmatrix} y_{ref}^1 \\ \vdots \\ y_{ref}^m \end{bmatrix}, x_{CP} \triangleq \begin{bmatrix} x_{CP}^1 \\ \vdots \\ x_{CP}^m \end{bmatrix} \quad (8)$$

Since (7) is true for any generator control set, one can simply obtain the local dynamical model for the entire region as

$$\dot{x}_{LC} = f_{LC}(x_{LC}, y_{ref}, x_{CP}) \quad (9)$$

where the nonlinear function is defined as

$$f_{LC}(x_{LC}, y_{ref}, x_{CP}) \triangleq \begin{bmatrix} f_{LC}^1(x_{LC}^1, y_{ref}^1, x_{CP}^1) \\ \vdots \\ f_{LC}^m(x_{LC}^m, y_{ref}^m, x_{CP}^m) \end{bmatrix} \quad (10)$$

## 2.6. Network Constraints

The transmission network imposes algebraic constraints on the coupling variable  $x_{CP}$  and a small subset of local state variables  $x_{LC}$ . With definition (8), it is demonstrated in [9] that the constraints are always given in the following structural form

$$g(x_{CP}, x_{LC}, F) = 0 \quad (11)$$

where the nonlinear function  $g(\cdot, \cdot, \cdot)$  has the same dimension as that of the coupling variables. The term  $F$  represents tie-line flows into the region from its neighboring regions. This formulation assumes constant power loads. Any variations in the loads are viewed as disturbances to the system. The primary goal of power system control design is to reject the load disturbances. The differential equation of local dynamics given in (9), together with this algebraic relationship, forms the dynamics of the system in the form of differential-algebraic equations (DAE).

It is well known that DAE problems are very difficult to handle in general. It is proposed here that the DAE problem is converted to ordinary differential equations (ODE), by differentiating the algebraic constraint equation (11) with respect to time. It follows that

$$J_{CP} \dot{x}_{CP} + J_{LC} \dot{x}_{LC} + J_F \dot{F} = 0 \quad (12)$$

where

$$J_{CP} \triangleq \frac{\partial g}{\partial x_{CP}}, \quad J_{LC} \triangleq \frac{\partial g}{\partial x_{LC}}, \quad \text{and} \quad J_F \triangleq \frac{\partial g}{\partial F} \quad (13)$$

are defined as the Jacobian matrices of the network constraints. Note that these Jacobian matrices are evaluated at the actual value of the state and flow variables  $(x_{CP}, x_{LC}, F)$ , and therefore no approximations are introduced.

To derive a standard state space ODE model for the dynamics of thereon, let us assume that the square matrix  $J_{CP}$  is nonsingular. If this is not the case, complicated phenomenon such as impasse points [3] will occur. This case is out of the scope of this paper and will not be further discussed. Under this condition, (12) can be equivalently written as

$$\dot{x}_{CP} = S_{LC}(x_{CP}, x_{LC}, F)\dot{x}_{LC} + S_F(x_{CP}, x_{LC}, F)\dot{F} \quad (14)$$

where

$$S_{LC}(x_{CP}, x_{LC}, F) \triangleq -J_{CP}^{-1}J_{LC} \quad \text{and} \quad S_F(x_{CP}, x_{LC}, F) \triangleq -J_{CP}^{-1}J_F \quad (15)$$

are defined as the sensitivity matrices of coupling variables to local states and flows, respectively. Again, these sensitivity matrices are functions of the state and flow variables, as explicitly indicated above. Eq. (14) represents an equivalent nonlinear ODE set for the network algebraic constraints.

## 2.7. Structural Dynamical Model

The local dynamical model (9), combined with the coupling dynamics given in (14), forms a complete set of ODEs for dynamics of the specific region under consideration,

$$\begin{bmatrix} \dot{x}_{LC} \\ \dot{x}_{CP} \end{bmatrix} = \begin{bmatrix} f_{LC}(x_{LC}, y_{ref}, x_{CP}) \\ S_{LC}(x_{CP}, x_{LC}, F)\dot{x}_{LC} + S_F(x_{CP}, x_{LC}, F)\dot{F} \end{bmatrix} \quad (16)$$

or,

$$\begin{bmatrix} \dot{x}_{LC} \\ \dot{x}_{CP} \end{bmatrix} = \begin{bmatrix} f_{LC}(x_{LC}, y_{ref}, x_{CP}) \\ S_{LC}(x_{CP}, x_{LC}, F)f_{LC}(x_{LC}, y_{ref}, x_{CP}) + S_F(x_{CP}, x_{LC}, F)\dot{F} \end{bmatrix} \quad (17)$$

Define the state variables in the extended state space for the region under study as

$$x \triangleq \begin{bmatrix} x_{LC} \\ x_{CP} \end{bmatrix} \quad (18)$$

and the nonlinear function on the right hand side of (17) as

$$f(x, y_{ref}, F, \dot{F}) \triangleq \begin{bmatrix} f_{LC} \\ S_{LC}f_{LC} + S_F\dot{F} \end{bmatrix} \quad (19)$$

We obtain the nonlinear standard state space dynamical model for any administratively divided region as

$$\dot{x} = f(x, y_{ref}, F, \dot{F}) \quad (20)$$

Notice that the reference values for output variables,  $y_{ref}$  are updated more slowly than the transient dynamics by a higher level control center. The purpose of updating the reference  $y_{ref}$  is to render an optimal performance of the system accommodating the slowly varying component of the load fluctuations (fast component of the load variations is stabilized by the appropriate design of local controllers). This typical implementation of the control, referred to in this paper as the hierarchical control structure, gives rise naturally to different time scales for the closed-loop dynamics. The following section will discuss the time scale separation associated with this particular structure.

Note also that this dynamical model is written explicitly in terms of tie-line flows into the region from neighboring systems. In (20), the tie-line flows act as an external input to the dynamics of the region under study. These flows play important roles in the inter-area behaviors of different regions within the interconnected system. It will be shown that the decoupled real power/frequency dynamics are not completely controllable under the present control structure; the local control  $u_{LC}$  cannot regulate inter-area behaviors of the interconnected system. The Popular, but not well-understood phenomenon of inter-area oscillations cannot be effectively suppressed with local governor controls, without significantly changing voltages throughout the network. In this case, additional control actions are needed to guarantee a desired performance of the system. This leads to the idea of direct flow control for which basic hardware is available at present [9].

## 2.8. Control-Induced Time Scale Separation

Because the updating of reference values of output variables is done typically more slowly than the time constant of the system transient dynamics, different time scales exist in the system dynamics over long time horizon. Time-scale separation techniques can be used to support higher-level control designs.

The linearized dynamical model for any administrative region as

$$\dot{x} = Ax + By_{ref} + UF + VF \quad (21)$$

In this equation, vector  $F$  represents the tie-line flows into this region from its neighboring regions. The reference value  $y_{ref}$  is updated, by either the local level or higher level controls, at discrete instants to regulate the profiles of output variables of direct interest so that some predefined optimality is achieved. Due to physical limitations and practical considerations, the updating is typically done more slowly than the transient dynamics. This process of updating the reference values of individual controllers is often called the *secondary control*. Let us denote the time interval of the secondary control as  $T_s$ , that is, the reference value is updated at instant  $kT_s$ ,  $k = 0, 1, \dots$ . Thus the reference value  $y_{ref}$  is constant in the interval  $kT_s < t < (k + 1)T_s$ . Let us further denote  $v_s[k] \equiv y_{ref}(kT_s)$  as a discrete time sequence of the reference value. With this notation, (21) can now be written as

$$\dot{x} = Ax + Bv_s[k] + UF + VF \quad (22)$$

The objective of secondary control is to design an appropriate discrete time sequence  $v_s[k]$  to achieve some prespecified optimality criterion at each subsystem level.

Because the discrete sequence  $v_s[k]$  varies more slowly than the transient dynamics, much simpler models can be derived to assist the secondary control design. Let us now carry out the detailed derivations. Because the time constant of the transient dynamics is much shorter than the secondary control time interval  $T_s$ , one can assume that all transient dynamics settle to a steady state before each time instance  $kT_s$ , that is,  $\dot{x} = 0$  at  $kT_s$ . Eq. (22) then reduces to

$$Ax + Bv_s[k] + UF = 0, \quad \text{at } t = kT_s \quad (23)$$

or

$$Ax[k] + Bv_s[k] + UF[k] = 0 \quad (24)$$

using the convention of (1). Eq. (24) determines a static relationship between the steady-state equilibria of the system and the reference values to be adjusted by the secondary control.

The secondary level controls are designed to eliminate the slower steady-state offset of some critical variables in the region under the slow drifting of disturbances. Let us express these critical variables for the secondary level as

$$x_s = Dx \quad (25)$$

The dimension of  $x_s$  is in general much lower than the dimension of  $x$ . The reference value  $v_s[k]$  is updated on the time scale  $T_s$  so that slower steady-state offset in  $x_s$  on the time scale  $T_s$  is eliminated. The desired relationship between  $x_s[k]$  and  $v_s[k]$  can be easily determined from (24) as

$$x[k] = -A^{-1}Bv_s[k] - A^{-1}UF[k] \quad (26)$$

and therefore

$$x_s[k] = B_s v_s[k] + M_s(F[k] - D_s d_s[k]) \quad (27)$$

with  $B_s \triangleq -DA^{-1}B$  and  $M_s \triangleq -DA^{-1}U$ .

Eq. (27) determines a quasi-static relationship between  $x_s[k]$  and  $v_s[k]$ . This quasi-static relationship is best utilized for the secondary control design when transformed into a dynamical model. To introduce the secondary discrete time dynamical model, let us subtract (27) at two consecutive time instances  $kT_s$  and  $(k+1)T_s$ :

$$x_s[k+1] - x_s[k] = B_s(v_s[k+1] - v_s[k]) + M_s(F[k+1] - F[k]) \quad (28)$$

Define the update of the reference value, or the corrective control for the secondary level as

$$u_s[k] = v_s[k+1] - v_s[k] \quad (29)$$

and the change of tie-line flows as

$$F_s[k] = F[k + 1] - F[k] \quad (30)$$

One obtains the secondary level discrete time dynamical model as

$$x_s[k + 1] - x_s[k] = B_s u_s[k] + M_s F_s[k] \quad (31)$$

Model (31) is introduced as the simplest model for designing output feedback-based secondary level controllers at the regional level. This model can also be interpreted as representing a discrete event process of a moving equilibrium  $x_s[k]$  driven by the discrete contraction  $u_s[k]$  and the tie-line flows [2]. Variables  $x_s[k]$  will be referred to as the *secondary level states*.

It should be pointed out that the corrective control signal  $u_s[k]$  defined in (29) represents an implicit integral control, because, from (29),

$$v_s[l] = \sum_{k=0}^{l-1} u_s[k] + v_s[0] \quad (32)$$

for any integer  $l$ . It is this implicit integral control that rejects the steady-state error in the output variables on the secondary level time scale.

### 3. HIERARCHICAL CONTROL DESIGN

In this section we present the hierarchical control design methodology based on the time-scale separation method discussed above. It is shown that the effect of neighboring regions can be easily accounted for in the regional control design, using the derived simple model at the secondary level.

#### 3.1. Controllability

Let us first show a structural property associated with a control-driven system—the controllability of the system is determined by the relative dimensions of the states and controls. Assume that the dimension of the secondary level states  $x_s[k]$  is  $n$ , and the dimension of the secondary level controls  $u_s[k]$  is  $m$ . Recall that the controllability matrix of (31), with  $F_s[k]$  treated as an external input, can be written as

$$[B_s \ 0 \ \cdots \ 0] \quad (33)$$

This matrix has maximum rows of  $m$  and therefore maximum rank of  $m$ . If the number of controls  $m$  is less than the number of states  $n$ , as is typically always the case, this controllability matrix is always singular, and the system is not fully controllable. This property is a structural one since it is independent of the numerical values of the system.

As a result of this structural uncontrollability, only at most  $m$  states can be controlled independently. Let us choose  $m$  critical states as the output variables to be regulated by the secondary control, expressed as

$$y_s[k] = C_s x_s[k] \quad (34)$$

with matrix  $C_s$  having dimension  $m \times n$ . Variations in the output variables  $y_s[k]$  can be easily obtained from (31) as

$$y_s[k+1] - y_s[k] = C_s B_s u_s[k] + C_s M_s F_s[k] \quad (35)$$

Define the  $m \times m$  square matrix  $U_s = C_s B_s$ . Then the above can be written as

$$y_s[k+1] - y_s[k] = U_s u_s[k] + C_s M_s F_s[k] \quad (36)$$

Under the further assumption that the number of controls and relevant outputs at each regional level is the same<sup>3</sup> one obtains an explicit recursive relationship between the controls, relevant output variables and flows of the form

$$v_s[k+1] - v_s[k] = L_1 y_s[k+1] - L_2 F_s[k+1] + L_3[k] \quad (37)$$

where

$$L_3[k] = -L_1 y_s[k] + L_2 F_s[k] + L_2 d_s[k] \quad (38)$$

### 3.2. Conventional Secondary Control

The goal of the secondary level control is to stabilize the output variables  $y_s[k]$  over the secondary time horizon to an optimal value determined by the tertiary control. The conventional secondary control takes the simple proportional form

$$u_s[k] = G(y_s[k] - y_s^{opt}[K]) \quad (39)$$

where  $y_s^{opt}[K] \triangleq y_s^{opt}(KT_t)$  is the optimal value for the output variables on the even longer tertiary time scale  $T_t$ . This optimal value is calculated by the tertiary control, and is constant for secondary processes.

Under this conventional feedback control, secondary level closed-loop dynamical model for output variables is obtained as

$$y_s[k+1] - y_s[k] = U_s G(y_s[k] - y_s^{opt}[K]) + C_s M_s F_s[k] \quad (40)$$

---

<sup>3</sup>This can be relaxed

The gain matrix  $G$  can be chosen to optimize a performance index at the regional level

$$J_s = \sum_{k=0}^{\infty} (y_s^T[k] Q y_s[k] + u_s^T[k] R u_s[k]) \quad (41)$$

for some matrices  $Q = Q^T \geq 0$  and  $R = R^T > 0$  specified by each region. The superscript  $T$  denotes the transpose of a matrix. The optimization is with respect to  $u_s[k]$ , and the result is the optimal gain matrix  $G$ . In this process, tie-line flows with neighboring regions are neglected, due to the large scale of the system and the desire to maintain decentralized nature of the regional control.

### 3.3. Improved Secondary Level Control

It is clear from (40) that tie-line flows viewed as an independent external input to the system affect the dynamics of the output variables. The conventional “optimal” control designed with interconnections neglected will no longer be optimal when implemented to the actual system where interconnections are indeed present. To fully compensate the effect of interconnections, we propose a modified feedback control law in the form

$$u_s[k] = G(y_s[k] - y_s^{opt}[K]) + H F_s[k] \quad (42)$$

where the term  $H F_s[k]$  is to cancel the effect of  $F_s[k]$  on output variables. Substituting (42) into (40) yields

$$y_s[k + 1] - y_s[k] = U_s G(y_s[k] - y_s^{opt}[K]) + (U_s H + C_s M_s) F_s[k] \quad (43)$$

It is clear that if  $U_s$  is invertible, then the effects of the tie-line flows can be fully eliminated by simply choosing

$$H = -U_s^{-1} C_s M_s \quad (44)$$

With this choice of  $H$ , (43) reads

$$y_s[k + 1] - y_s[k] = U_s K_s (y_s[k] - y_s^{opt}[K]) \quad (45)$$

with no flows entering into the equation. In other words, the region under study looks as if it were fully isolated from the rest of the system, as far as the output variables are concerned.

Note that the condition that  $U_s$  is invertible should not be viewed as restrictive; instead, it ought to be taken as one of the requirements for the choice of output variables. This is due to the fact that the matrix  $(I + U_s K_s)$  is the system matrix for the output variables  $y_s[k]$  seen from (40) or (45); therefore, if the matrix  $U_s$  were singular, the closed-loop system matrix  $(I + U_s K_s)$  would always have an eigenvalue of 1. The consequence of this is that steady state errors are inevitable for the chosen output variables. To fully control all output variables, it is required that they are selected such that  $U_s$  is of full rank.

Note also that the control scheme presented here is totally decentralized, assuming that tie-line flows are locally measurable at each region level. No detailed information about neighboring regions is needed; only tie line flows are required, since they aggregate the net effect of detailed dynamics of neighboring regions. It is not an unrealistic assumption that tie-line flows are locally measurable.

### 3.4. Quasi-Static Interaction Variables

The secondary quasi-static dynamical model for any region explicitly in terms of the tie-line flows has been derived as 28 where  $x_s[k]$  is the state vector representing all buses in the region. The dimension of the sensitivity matrix  $B_s$  is  $n \times m$ , with  $n$  being the total number of buses in the region, and  $m$  the number of generator buses that participate in the secondary level regulation. In general it is true that  $n > m$ , that is, the number of load buses is larger than the number of generator buses participating in the secondary level control.

Under the condition of  $n > m$ , one can easily verify that the closed-loop system using any feedback control is singular, because matrix  $B_s$  has maximum rank of  $m$ . This structural singularity due to the relative numbers of controls and states. This is a general property for any control-driven systems. In exploiting this structural singularity of the quasi-static voltage dynamics, we first give the following definition.

**DEFINITION 1. (Quasi-Static Interaction Variables).** Any linear combination of the states,  $z[k] = Tx[k]$ ,  $T \neq 0$ , that satisfies

$$z[k+1] - z[k] \equiv 0, \quad \forall k \quad (46)$$

for any secondary control actions, and in the absence of interactions among regions and the disturbance, that is,  $F_s = 0$  and  $d_s = 0$ , is defined as the quasi-static interaction variable of the administrative region under study.

The quasi-static interaction variables do not vary with time when interconnections are removed and load disturbances are not present. For the interconnected system, therefore, any variations of the interaction variables with time are entirely due to the interactions among regions or load disturbances. It should be noticed from the definition that the interaction variables are not unique. In fact, any combination of the interaction variables is still a set of interaction variables.

Let us derive the condition for the transformation matrix  $T$ . Combining (46) and (28) yields

$$z[k+1] - z[k] = TB_s u_s[k] + TD_s(F_s[k] - d_s[k]) \quad (47)$$

Under the conditions in the definition,  $F_s[k] \equiv 0$  and  $d_s[k] \equiv 0$ , we arrive at

$$z[k+1] - z[k] = TB_s u_s[k] \quad (48)$$

In order to have  $z[k+1] - z[k] \equiv 0$  for any control  $u_s[k]$ , matrix  $T$  must satisfy

$$TB_s = 0 \quad (49)$$



This is the desired equation for calculating  $T$ . Note that matrix  $B_s$  has maximum rank  $m < n$ , and therefore, equation (49) has nonzero solutions for  $T$ . It is quite easy to solve  $T$  from (49), since it is a simple algebraic equation, and can be solved using Gauss elimination method. The need for eigenstructure analysis is completely avoided.

Note that the definition for interaction variables is for any secondary control, meaning that the interaction variables are independent of the specific secondary control. Equivalently, the secondary control cannot affect the interaction variables. Any variations of the interaction variables are uniquely due to the interactions with other regions or the load variations. The matrix  $T$ , as a result, will not be dependent on the specific form of the secondary control.

Once the interaction variables are determined from (49), one can further derive the dynamical model for these interaction variables. Eqs. (47) and (49) simply lead to

$$z[k + 1] - z[k] = TD_s(F_s[k] - d_s[k]) \quad (50)$$

This is the desired dynamical model for the interaction variables. This simple model relates the interaction variables to the tie-line flows and load variations. It is of crucial importance for the secondary control and tertiary level coordination, as is discussed in more detail below.

Notice that the definition for interaction variables does not assume numerically weak interconnections. Rather, it reflects a structural property of the system, different numbers of the states and controls. It is interesting to relate the interaction variables defined above to the slow variables in singular perturbation analysis when the interconnections are indeed weak. It is easily seen from the interaction dynamical model (50) that, in the weak interconnection case, the interaction variables do vary more slowly than the rest of the states. One can rigorously prove that, in the weak interconnection case, the interaction dynamics derived here will be the slow subsystem in the singular perturbation analysis.

For illustration of the interaction variables see [9]. To summarize, this section presents a structurally based modeling approach for dynamics of an interconnected power system. Dynamics of the system are formulated by combining the local dynamics of individual generators and the network couplings. Quasi-static dynamical models on slower time scales are derived. The structural models developed here has been used to define systemwide voltage control on slower time scales according to performance specifications at each regional level [12]. Both conventional and improved secondary voltage control are studied using this framework.

#### 4. TERTIARY COORDINATION

With an increased tendency toward large energy transfer over long distances, the problem of maintaining voltages and frequency within the acceptable operating specifications has merged in operating and planning power systems throughout the world.

The main purpose of the tertiary level controls is to update set values for tie-line power flows  $F[K]$ ,  $K = 0, 1, \dots$  on the tertiary level time scale in order to optimize systemwide

performance for the anticipated base load  $P_L[K]$  and  $Q_L[K]$ ,  $K = 0, 1, \dots$ . This could be done on hourly basis, if not more often in accordance with the statistical information on base load. The actual setting of tie-line flows is achieved by changing settings of secondary controllers. Because this is done so infrequently, it could involve recomputing of basic matrices around a new operating point for the anticipated load over the time horizon  $T_r$ .

The optimization problem for the optimal set values can be formulated for three basic architectures (industry structures):

- *Fully centralized*: The coordination tasks are performed by a global coordination center which has available full information. The entire interconnected system is modeled as a single region. One single performance criterion is optimized, and the optimal set values for all regions are obtained.
- *Fully decentralized*: The determination of set values of the pilot voltages is done by each individual region itself. Each region optimizes its own performance criterion. Each region does not assume any information about the rest of the system. In the optimization process of each region, the tie-line flows into the region are measured and used to determine the optimal pilot voltage set values for the region.
- *Partially centralized/decentralized*: In this scheme, each region assumes limited information about the rest of the system, and, with the limited information, tries to optimize its own performance criterion. The natural choice for the limited information about the rest of the system is simply the aggregate model developed previously. We model this scenario in a game-theoretical setting.

The systemwide performance criterion for the fully centralized methods is, in general, quite difficult to establish, and the computational effort for the solution is enormous, as the power system is very large. Therefore the coordination scheme cannot be implemented quite often. The fully centralized methods also require global communication over far distances. The fully decentralized or partially centralized/decentralized schemes, on the other hand, have obvious advantages. There is an extensive degree of handling specific problems of different regions with different performance criteria. This is particularly suitable for a multi-utility environment. The performance criteria for smaller regions are easier to obtain, and the computational work is significantly reduced. As a result, no global communication is required, and the coordination schemes can be implemented relatively more frequently. The major disadvantage of the schemes with competition nature is that instability can occur.

Due to the large size of the system and complexity of the system operation, any practical on-line coordination schemes must be based on a reduced-information structure in order to be applied efficiently. In this paper, we develop a tertiary coordination scheme, based on a reduced-information structure, using the interaction variables defined in the previous section. The defined interaction variables represent the inter-area tie-line power flows, and serve as a basis for the inter-area coordination. We shall derive an important relationship between the quasi-static interaction variables and the set values of critical outputs at each regional level.

## 5. NEW TERTIARY LEVEL AGGREGATE MODELS

Using the structural modeling approach described above, one can derive the relationship between the critical subsystem outputs at each regional level and the regional controls, the relationship between the flows and the interaction variables, and the relationship between the flows and the output variables, on the tertiary level time scale  $T_t$ . These relationships serve as constraints to the optimization problem for determining optimal set values for the most relevant output variables. Here only the most relevant relations in context of this paper are described. For others, see [9]

### 5.1. Centralized Aggregate Models

In this subsection, the global interconnected system is considered as one single region. Since this big single region is an isolated system, there are no tie line flows into the system. All previous derivations carry over to the global interconnected system, except all tie-line flow terms drop out.

We use the boldface italic letters to represent any variable associated with the global interconnected system. For example, let us define  $\mathbf{v}_s$ , and  $\mathbf{y}_s$  to represent the critical output variables of the global system. The relationship between the critical outputs and controls is in the same form as (37)–(38)

$$\mathbf{v}_s [K + 1] = L_1 \mathbf{y}_s [K + 1] + L_3 [K] \quad (51)$$

where

$$\mathbf{v}_s [K] = L_3 [K] - L_1 \mathbf{y}_c [K] + L_2 \mathbf{d}_t [K] \quad (52)$$

Comparing with Equation (37)–(38), we observe the absence of the flow term, because the global system is assumed to be an isolated one, and there is no flow for the isolated system.

The rudimentary economic models describing cost processes associated with the controls at both tertiary and secondary levels are described in [15]. Conceptually, they are derived by mapping the control sequence performed into its cost sequence. It is essential to combine these two processes for a coordinated technical and economic performance of these controllers. The authors are continuing work into this direction.

*5.1.1. Flows and the critical output voltages at the interconnected system level.* The relationship between the internal flows among the regions within the global system and the critical output variables is obtained by combining (51) with the model (37)–(38) written for all regions. Its general form is

$$S(F[K + 1] - F[K]) = L(\mathbf{y}_s[K + 1] - \mathbf{y}_s[K]) + L_d \mathbf{d}_t [K] \quad (53)$$

This model is referred to as the tertiary level model, which relates explicitly the interaction variables among the regions and the critical output variables in the interconnected system. One should observe a difference between this model and the model expressed explicitly in terms of flows. The latter is not possible, implying that at the interregional level only interaction variables can be set explicitly, and not individual tie-line flows.

## 6. OPTIMALITY OF DECENTRALIZED MANAGEMENT AND ITS LONG-TERM STABILITY

The formulation and proofs in this section are essential for beginning to differentiate among the ways system optimization in a deregulated utility environment is formulated at present, and the most likely ways in the future. It is emphasized here that these issues are typically not well thought through and, therefore, not appreciated. As a result, much confusion arises in interpreting how the future energy management should be done.

Consider any administratively separated region  $i$  within an interconnected system. Let the control variables be  $u^i$  (real power generation settings or voltage settings), state variables be  $x^i$  (frequencies and voltage of loads). The task of controllers at a subsystem level is to determine  $u^i$ , in order to minimize a cost function defined in equation (41), restated here as:

$$J^i = J^i(y^i, u^i) \quad (54)$$

where  $i = I, II, \dots, R$ , assuming there are  $R$  regions in the system.

Using the structure-based modeling approach from [10] and reviewed briefly above, the outputs  $y^i$  and controls  $u^i$  at each subsystem level shown to be related as (28) and restated here for simplicity as

$$y^i = A^i u^i + B^i F^i + L_0^i \quad (55)$$

where  $A^i, B^i$  are system constants,  $L_0^i$  is a function of the system condition at the previous step, and  $F^i$  is the tie-line flows into the region  $i$ , one could pose necessary conditions for constrained optimum in a distributed environment. This is described next.

### Case A—Decentralized Optimization

In the decentralized, each region optimizes its own cost function  $J^i$ . It is straightforward to show that the necessary optimality condition at the equilibrium is given as

$$\frac{dJ^i}{du^i} = \frac{\partial J^i}{\partial u^i} + \left[ \frac{\partial y^i}{\partial u^i} \right]^T \frac{\partial J^i}{\partial y^i} = 0 \quad (56)$$

Using (55), one obtains

$$\frac{\partial J^i}{\partial u^i} + \left[ A^i + B^i \frac{\partial F^i}{\partial u^i} \right]^T \frac{\partial J^i}{\partial y^i} = 0 \quad (57)$$

Comparing with the centralized method, we see that all

$$\frac{\partial y^i}{\partial u^j} \quad j \neq i \quad (58)$$

are neglected in the distributed optimization.

Different ways of treating  $\partial F^i/\partial u^i$  yield different results. We propose two strategies:

(i) *Constant-flow strategy*. In this strategy, flows are viewed as a measured parameter; thus, all derivatives of the flow with respect to controls are neglected, that is,

$$\frac{\partial F^i}{\partial u^j} = 0 \quad \forall i, j \quad (59)$$

(ii) *Nash strategy*. In this game strategy, flows are viewed as function of the controls in its own region. As a result, all cross-derivatives of the flow with respect to controls in other regions are neglected—equivalent to the so-called “reaction curves”.

Neglecting  $\partial Dy^i/\partial u^j$ ,  $j \neq i$ , we have

$$\frac{\partial F^i}{\partial u^i} \neq 0 \quad (60)$$

These two decentralized optimization problems have different solution. Their relationship is easily seen as that letting  $\partial F^i/\partial u^j = 0$  in the Nash solution yields the constant-flow solution. The above mathematical derivations are essential for understanding the limitations of decentralized energy management. Only in the very particular case when individual performance criteria are functions of controls will the decentralized and centralized optimization in a multi-utility environment lead to the same optimum value. This means that a general competitive, decentralized setup will entail deviations of the interconnected system from its ideal optimum performance.

The general solution form of both decentralized optimization processes can be written as

$$u^i = f^i(F^i) \quad (61)$$

## 6.1. Achievable Optimality as a Function of Controls/Management Structure

Here for the first time a mathematical formulation needed to quantify systemwide deviations from the ideally achievable optimum in power systems is proposed. The necessary optimality conditions are strongly dependent on the type of information exchange available. While Case A above is concerned with different implementations of a competitive, decentralized management, Case B below provides an interpretation of a centralized optimum in terms of flow sensitivities explicitly.

### Case B—Centralized Optimization

Assume that the centralized cost function is the sum of all regional cost functions, that is,

$$J[K] = \sum_{i=1}^R J^i[K] \quad (62)$$

and assume that all information needed for centralized optimization is available for all regions. One has

$$\frac{dJ}{du^i} = \frac{\partial J^i}{\partial u^i} + \sum_{i=1}^R \frac{\partial J^i}{\partial u^i} \quad (63)$$

$$= \frac{\partial J^i}{\partial u^i} + \sum_{i=1}^R \sum_{k=1}^R \left[ \frac{\partial x^k}{\partial u^i} \right]^T \frac{\partial J^i}{\partial x^k} \quad (64)$$

$$= \frac{\partial J^j}{\partial u^j} + \sum_{i=1}^R \left[ \frac{\partial x^i}{\partial u^j} \right]^T \frac{\partial J^i}{\partial x^i} \quad (65)$$

Note the presence of the cross-terms  $\partial x^i / \partial u^j$ , which can be obtained from

$$x^j = A^i u^i + B^i F^i + L_0 \quad (66)$$

$$\frac{\partial x^j}{\partial u^i} = \begin{cases} A^i + B^i \frac{\partial F^i}{\partial u^i} & j = i \\ B^i \frac{\partial F^i}{\partial u^j} & j \neq i \end{cases} \quad (67)$$

This optimum can be used as the ideal achievable optimum for comparison of solutions obtained in a distributed manner.

## 7. CONCLUSIONS

Drastic changes in electric power industry throughout the world are reflected primarily in competitive energy supply and demand. Much nontechnical and semitechnical literature is available on this [14]. While in the past technical functions of very-large-scale dynamical systems have been organized in a hierarchical way, the underlying mode has been one of cooperation, and not active competition. With the increased competition across the interconnected system, including non-utility-owned generation, the performance objectives are truly changing.

The emphasis is and it will be more so in the future on distributed decision making. The impact of this change is far reaching regarding both technical concepts for system operation and the economic incentives. One cannot forget that the power systems are a happy compromise of good technical performance and economic efficiency. It is more so today than ever before that these two attributes could become truly exclusive. One needs a mathematical framework study both problems, as well as their interplay.

The economics of interest is different than in the past. Each participant in the competitive energy market needs to educate itself regarding its meaningful value in the process, and create a price feedback to the other players.

The problem is to model in a simplest possible way, with minimum information structure, the distributed processes and their dynamics.

Starting with an interconnected system as a whole, this is a very challenging problem, since it is necessary to have models interpretable at each level in terms of actual physical variables.

The next unique attribute of the mathematics needed is in terms of time scales of interest. Traditionally dynamical models used in power systems have been used either for analyzing very short-term responses (transients) or only stationary operation. It turns out that the most interesting and relevant processes are the processes of moving equilibria over time horizons in which system inputs change as driven by economic inputs.

These models are essential to even begin to study relations between economic processes and technical processes, including controls needed over such time horizons to keep the interconnected system together.

The longer time scales are particularly pronounced at the secondary and tertiary system levels. The theoretical framework needed is the one which naturally lends itself to both present horizontal system architectures, as well as to the architectures which are likely to evolve under the competition.

In this light, a modeling and control framework which provides models at different levels of hierarchy is useful for both coordinated control design with the performance objectives different at different levels, yet consistent with the systemwide performance objectives; it is also essential for formulating processes under competition. One such modeling and control framework described above uniquely lends itself to the problem formulations in the competitive power industry.

This is so because the secondary level model, which could be thought of as representing each individual player is expressed in terms of local states and controls associated with this level, and in terms of interaction variables with the other players.

A distributed decision-making takes place without any tertiary level coordination. The problem of technical performance becomes the one of fully distributed controls at the secondary level with individual objectives.

It is conceptually possible to set up different decision-making processes by means of the developed secondary level models in order to study stability over the long term horizons (typical of tertiary level in the traditional environment).

Even more importantly, one could study optimality of the interconnected system as a function of competitive structure. Some initial results on this can be found in [9].

It is believed by the authors of this paper that the structural modeling described can be used for efficient game-theory-like formulations of many problems of direct interest to the power industry. The first author of this paper is actively working in this area.

Finally, the most intriguing aspect of the proposed model is its ability to capture both technical and economic processes over the time horizons  $T_i$ . One could think in terms of value to each market player (subsystem) in a very straightforward way as [13]

$$TV^i [KT_i] = \sum_k J^i(x^i, u^i, F^i) - J^i(x^i, u^i, F^i = 0) \quad (68)$$

A competitive economic market will reach an equilibrium when these technical values of all players are equalized. The problem of participating in a competitive energy market

and stay a winner has much to do with knowing what this value is. A price associated with this quantity at the economic equilibrium, provided it is unique and it exists, is well known in economics as the *market price*.

The power-systems community faces an enormous challenge and opportunity in formulating and solving the operating and pricing strategies in this light. This sudden change in thinking from centralized optimization of the system to gaming is neither easy on practicing engineers, nor on researchers.

### *Acknowledgment*

This work was partially supported by a grant from the United States Department of Energy, Office of Utility Technology, under grant number DE-FG41-92R1104447.

### *References*

1. Ewart, D. N., Automatic generation control: Performance under normal conditions, *Proc. of the systems engineering for power: Status and prospects*, Henniker, NH, August 1975.
2. Siljak, D., *Large-scale dynamic systems*, Elsevier North-Holland, New York, 1978.
3. Hill, D., and I. Marcelis, Stability theory for differential/algebraic systems with applications to power systems, *IEEE Trans. on Circuits and Systems*, **CAS-37**, (11), (November 1990), 1416–1423.
4. Chow, J., Time-scale modeling of dynamic networks with applications to power systems, Springer-Verlag, New York, 1982.
5. Nash, J. F., Jr., Equilibrium points in N-person games, *Proc. Nat. Acad. Sci. U. S.*, **36**, (1950), 48–49.
6. Cruz, J. B., Jr., Survey of Nash and Stackelberg equilibrium strategies in dynamic games, *Ann. Econ. Soc. Meas.*, **4**, (1975), 339–344.
7. Basar, T., On the uniqueness of the Nash solution in linear quadratic differential games, *Int. J. Game Theory*, **5**, (1976), 65–90.
8. Ilić, M. D., *Modern approaches to modeling and control of electric power systems*, Academic Press, New York, 1991.
9. Liu, X. S., Structural modeling and hierarchical control of large-scale electric power systems, M. I. T. PhD Thesis, Mechanical Engineering, April, 1994.
10. Ilić, M. D., B., Eidson, X. S., Liu, and M., Athans, A new structure-based approach to the modeling and control of electric power systems—Part I: Generation control and frequency regulation in response to slow load variations, under the review for the IFAC Automatica, (revised version submitted in July 1993).
11. Ilić, M. D., X. S., Liu, B., Eidson, and M., Athans, A new structure-based approach to the modeling and control of electric power systems—Part II: Voltage regulation and system-wide voltage coordination in response to slow load variations, under the review for the IFAC Automatica, (revised version submitted in July 1993).
12. Liu, X. S., M. D., Ilić, M., Athans, C., Vialas, and B., Heilbronn, A new concept of an aggregate model for tertiary control coordination of regional voltage controllers, *Proc. of the IEEE Conf. on Decision and Control*, Tuscon, December, 1992.
13. Ilić, M. D., Performance-based value of transmission services for competitive energy management, *Proc. of the 26th North American Symp. (NAPS)*, Manhattan, KS, September 26–27, 1994.
14. Graves, F. P., Carpenter, M.D., Ilić, and A., Zobjan, Pricing of electricity network services to preserve network security and quality of frequency under transmission access, Response to the Federal Energy Regulatory Commission's Request for Comments in its Notice of Technical Conference Docket No. RM93-19-000.
15. Eidson, B., and M., Ilić, Technical Enhancements of Controls in Power Systems Under Competition, *Proc. of the American Power Conf.*, April 18–20, 1995, Chicago.





# Hindawi

Submit your manuscripts at  
<http://www.hindawi.com>

