On the Control of Re-Structured Electric Power Systems

Ali Feliachi

Abstract: The paper describes some of the challenges that face the control of nonlinear interconnected power systems. The challenges include the selection of appropriate control and information structures that could range from a completely decentralized to a fully centralized structure. Once a structure is proven to be feasible, the effectiveness of control signals needs to be assessed. Analytical tools are derived for this purpose in the first part of the paper, and they are illustrated with a case study that involves the design of a damping decentralized controller using a Thyristor Controlled Series Compensation device. The second part of the paper deals with the load following and tracking problem through automatic generation control for a system that has been re-structured or deregulated. This problem can be solved using a completely decentralized scheme. It is solved here using fuzzy rules and with an emphasis on compliance with NERC's standards and reduction of wear and tear of the equipment. It is illustrated with a test system that has three interconnected control areas. Finally, comments on the economics of control and the author's vision are presented.

Keywords: Decentralized control, load frequency control, power systems, stability.

1. INTRODUCTION

The National Academy of Engineering ranks electrification as the greatest engineering achievement of the 20th Century. Many studies relate directly the standard of living to the electricity used per capita. The complex human-made power system was designed for vertically integrated utilities that own generation, transmission and distribution facilities. On April 24, 1996, the US Federal Energy Regulatory Commission (FERC) issued Order 888, a ruling on open access transmission, now known as electricity deregulation, or restructuring. The ruling has increased competition in wholesale power markets and has encouraged states around the nation to open retail electricity markets. Large vertically integrated utilities providing power at regulated rates are being restructured to incorporate competitive companies selling unbundled power.

Ali Feliachi is the Director of the Advanced Power and Electricity Research Center (APERC) at West Virginia University, P.O. Box 6109, Morgantown, WV 26506-6109, USA (e-mail: alfeliachi@mail.wvu.edu).

Consumers were supposed to benefit from lower rates, expected as a result of serious competitive bulk power markets. Unfortunately, some regions of the country have seen larger electricity bills and/or experienced poor power quality in terms of blackouts and/or brownouts. Blackouts are very costly. The last major one, which occurred on August 14, 2003, and affected the northeastern US and neighboring Canadian regions, is estimated to have cost more than five billion dollars. New players with different and sometimes opposing objectives have emerged. The already complex engineering system has to include economics, business, social and environmental aspects. To avoid market power, FERC issued a Notice of Proposed Rulemaking on Market Structure Design in July 2002. The task is formidable and the existing control and operation tools and practices do not mesh well with the national objective that can be phrased as "keeping the lights on at a reasonable cost."

Deregulation is affecting all business aspects of the power industry from generation to transmission. Investor–owned electric utilities, rural electric cooperatives, coal producers and coal hauling railroads are committed to meeting the nation's need for reliable electricity for the foreseeable future. Electricity demand is going up due to a thriving domestic economy, higher natural gas prices, increasing coal exports and growing pressure on world energy supplies from the booming Chinese economy. According to a 2002 data, US coal supplies 50% of the electricity used in the US; with Nuclear, Natural Gas, Hydro/Renewables and fuel oil in a 20.3, 18.1, 9.1 and 2.4 percent respectively. Coal will

continue to be the optimal choice for generation as research in clean coal technology produces plants that are cleaner and more efficient. Competition from natural gas plants in the form of integrated combined cycle gas turbine units, fuel cells and other distributed generating plants may present profitable alternatives to investors and help enhance the security of the critical electric power system infrastructure. This mix of new plant types presents an enormous control problem for area and regional operators. These decisions will affect the current transmission network which has seen investment declining over the past 25 years at a rate of $103 million per year. Over this same period electricity sales nearly doubled. These circuits are exceeding their thermal limits requiring that their stability be alleviated and increased. Congestion relief measures are crucially needed. Stress on the existing system has been partially blamed for the now historic August 14, 2003 blackout. Independent System Operators (ISOs) or Regional Transmission Owners (RTOs) will oversee and control very large systems, and they will attempt to make the integrated system work. Also, customers are expected to use the electricity judiciously taking into account the actual price of energy which may no longer be fixed throughout a given period. Questions remain on who will pay or invest in the control of the system, and what will be the control structure itself? Will shaving the peak demand thru load control, for example, pay for the investment over the long run? The latter could be argued that payment on the investment be determined by:

• Utility economics which uses pro-forma analysis to settle on approaches to the effective hurdle rate for decision making

• Methods that help determine effective load control using pricing signals that allow customers keep their HVAC systems in a comfort zone which has strong price parameters, especially on peak load periods. These controls can essentially flatten the peaks and reduce peak power plant sales from gas turbines.

• Customer metering is still predominately interval metering which determines, by kWHr metering, a block of kilo-watt-hours at an agreed upon price. Commercial and industrial customers have demand metering available which sets their cost-of service rates. Systems are developing which can send price signals to all customer classes allowing for both voluntary and mandatory load control, based on economics, which satisfy both customers and electric suppliers.

The dynamics of the power system following considerable structural changes (loss of a transmission line or a large generating unit) and loading conditions need to be controlled in order to insure system's integrity. These events can create dynamic instabilities in a fraction of a second. Some of these instabilities are related to instabilities in rotor angle, rotor speed, short and long-term voltage, and/or frequency.

Deregulation is expected to introduce new challenges in controlling and coordinating electric power systems. As ownership boundaries are drawn with each entity aiming at economic profits, it is very likely that an uncoordinated control system will result in serious economic losses with reduced reliability and inferior quality. On the other hand, a well-coordinated control system can be significantly beneficial to all participants. But, the complex characteristics of the power system make the analysis and the design of control systems a very challenging problem. The challenge is to understand the effects of deregulation on control strategies and to design and coordinate intelligent distributed controllers to effectively operate the power system, and make the system as autonomous as possible. Conventional and existing analytical tools may not be applicable to such complex power systems. Optimal operation requires design and coordination of integrated computing, communication and control systems that can handle continuous and digital, adaptive, reliable and robust distributed control schemes. The Independent System Operator or the Regional Transmission Owners will have the important task of coordinating controllers that might belong to other independent generating companies or transmission companies. The questions that are of primary importance are the following:

1. What is the control and information structure?
2. What are the control design challenges?
3. What are the economics of control?

This paper addresses some of these issues. In section 2, control and information structures ranging from a fully centralized to a completely decentralized structure are presented. Section 3 describes effective signal selection and design of damping controllers with a case study involving the design of a Thyristor Controlled Series Compensation damping controller [11]. Section 4 deals with the load following and tracking problem through automatic generation control which is solved using fuzzy rules with an emphasis on compliance with NERC's standards and reduction of equipments' wear and tear. It is illustrated with a test system that has three interconnected control areas [12]. Finally, comments on the economics of control and the author's vision are presented in section 5.

2. CONTROL AND INFORMATION STRUCTURES

Several robust control design tools exist for small systems for which a mathematical model and a performance index are identified. A global optimization
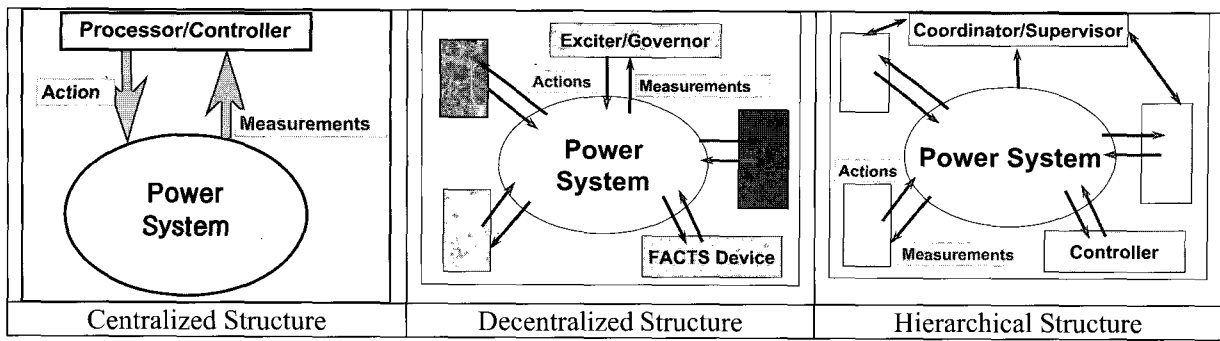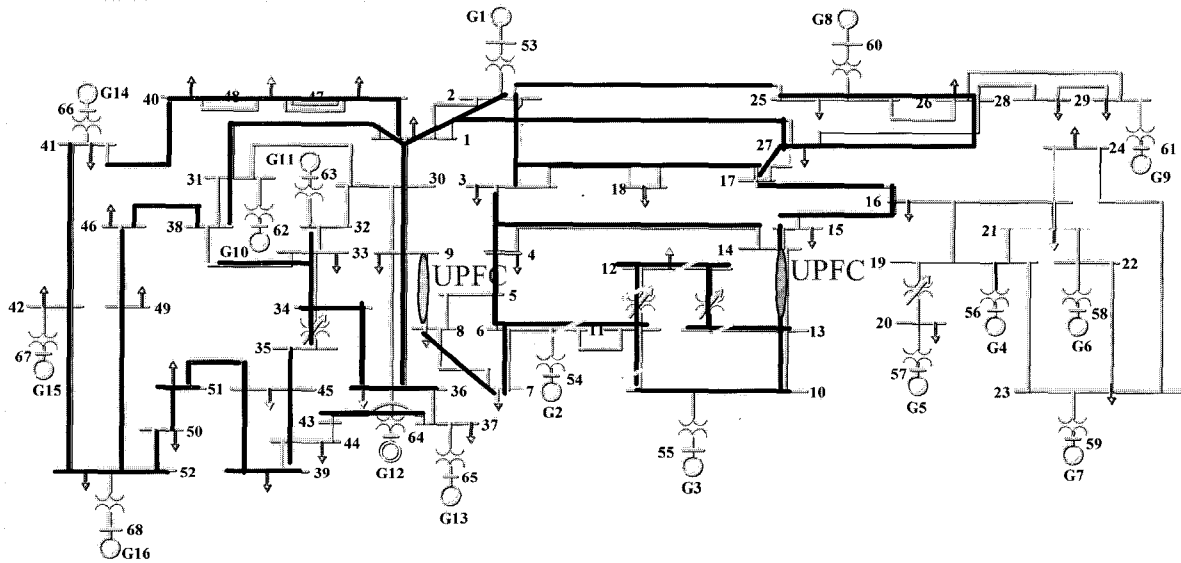
Fig. 1. Control structures.

Fig. 2. Effects of UPFCs on line flows.

can then be achieved which will be in terms of a centralized feedback controllers that is either a full state feedback or an observer based controller. Extending this to the power system is not obvious as the structure of the controller becomes unfeasible.

Decentralized structure is far more attractive for implementation, but will it work? In the case of Automatic Generation Control, a decentralized controller based on what is called the Area Control Error has been a common practice. For other problems such as damping inter-area oscillations, a decentralized structure might or might not work depending on the sensors and actuators that are deployed. For years, the WSCC system has exhibited poorly damped oscillations of a frequency around 0.7 Hz. The author has developed a tool to mathematically prove that it is a fixed mode and the decentralized control structure used at that time will not dampen these oscillations. This is a fundamental problem. Another alternative will be to use a hierarchical control scheme with distributed controllers at a lower level and a coordinator at a higher level.

Power systems consist of an interconnection of

numerous apparatus spread over a wide geographic area. A centralized control scheme amounts to gathering information about the entire system in one central location, processing this information to obtain control signals and then sending them back to the appropriate actuators. This is a tremendous amount of information exchange and computational efforts. A more appealing structure is a completely decentralized structure where local information is gathered and processed, but this ideal structure might or might not work. If the latter structure is not feasible, then a hierarchical structure will be the alternative. These three structures are shown schematically in Figure 1.

Activating a control device can have either a local or a global effect. For example, placing Unified Power Flow Controllers (UPFC) in a system will affect several nearby lines, as shown in bold face in Fig. 2. Hence, it is essential to determine a path between a control signal and all variables that could be affected by this signal. This will determine the feasibility of the control structure sought, and result in selecting the appropriate sensors, actuators and communication links. The author and his colleagues have developed the following analytical tools for this purpose.

3. EFFECTIVE SIGNAL SELECTION AND DESIGN OF DECENTRALIZED CONTROLLERS

Analytical tools are presented to determine the effectiveness of control signals in damping a pre-specified set of eigenvalues or critical modes, and also to determine the effects of a given feedback signal on the remaining eigenvalues. The goal is to design a controller to shift a critical mode or eigenvalue without worsening the damping of the remaining modes. This is an important problem in designing decentralized controllers. Since the system at hand is nonlinear, then the proposed design has to be effective for a wide range of operating conditions.

3.1. Problem formulation and modeling

Consider an interconnected system P with N control stations. Its state space model is of the following form:

$$\dot{x}(t) = f(x) + \sum_{k=1}^{N} g_k(x)u_k(t), \tag{1}$$

$$y_k(t) = h_k(x); \qquad k = 1,2,\cdots N$$

where x is a (nx1) state vector,
u_k is a $(r_k x1)$ control input vector at station k,
y_k is an $(l_k x1)$ output vector at station k.

The objective is to control the system over a range of m operating conditions. When this system is linearized around these operating points, m linearized models ($P_1(s)$, $P_2(s)$, ..., $P_m(s)$) are obtained. The state space representations of the system linearized around the i-th operating point $P_i(s)$ is described with:

$$\dot{x}^i = A^i x^i + B^i u^i, \tag{2}$$

$$y^i = C^i x^i$$

where
$$u^i = \begin{bmatrix} u_1^i & u_2^i & \cdots & u_N^i \end{bmatrix},$$

$$y^{iT} = \begin{bmatrix} y_1^{iT} & y_2^{iT} & \cdots & y_N^{iT} \end{bmatrix}.$$

The input vector u^i and the output vector y^i are of dimensions rx1 and lx1, respectively, where

$$r = \sum_{k=1}^{N} r_k \quad \text{and} \quad l = \sum_{k=1}^{N} l_k.$$

The corresponding input and output matrices are:

$$B^i = \begin{bmatrix} \mathbf{B}_1^i & \mathbf{B}_2^i & \cdots & \mathbf{B}_N^i \end{bmatrix},$$

$$C^{iT} = \begin{bmatrix} \mathbf{C}_1^{iT} & \mathbf{C}_2^{iT} & \cdots & \mathbf{C}_N^{iT} \end{bmatrix}.$$

The linearized model can be transformed to its modal form using the modal matrix $V^i = \begin{bmatrix} v_1^i & v_2^i & \cdots & v_n^i \end{bmatrix}$, i.e. the matrix of right eigenvectors, as a similarity transformation. In the

new coordinates, the modal system is described with:

$$\dot{\alpha}^i = \Lambda^i \alpha^i + \Gamma^i u^i, \tag{3}$$

$$y^i = \Omega^i \alpha^i,$$

where $\Lambda^i = W^i A^i V^i$, $W^i = (V^i)^{-1}$,

$$\Gamma^i = W^i B^i = \begin{bmatrix} w_1^{iH} B^i \\ w_2^{iH} B^i \\ \vdots \\ w_n^{iH} B^i \end{bmatrix}. \tag{4}$$

The controllability indices are obtained from the rows of (4). The j-th mode of the system is controllable if $w_j^{iH} B^i$ is a nonzero vector. $\left| \Gamma_{jk}^i \right|$ indicates the relative controllability of the j-th mode through the k-th input.

Similarly, the observability indices are found from the columns of the matrix Ω, which is given by:

$$\Omega^i = C^i V^i = \begin{bmatrix} C^i v_1^i & C^i v_2^i & \cdots & C^i v_n^i \end{bmatrix}. \tag{5}$$

The j-th mode of the system is observable if $C^i v_1^i$ is a nonzero vector. $\left| \Omega_{kj}^i \right|$ indicates the relative observa-bility of the j-th mode in the k-th output.

Assume that all of the eigenvalues of the matrix A^i are distinct, then the open loop transfer function $G^i(s)$ can be expressed in terms of residues:

$$G^i(s) = \sum_{j=1}^{n} \frac{R_j^i}{s - \lambda_j}, \tag{6}$$

where R_j^i is an(lxr) residue matrix associated with λ_j and it is given by:

$$R_j^i = \Omega_j^i \Gamma_j^i = C^i v_j^i w_j^{iH} B_i. \tag{7}$$

Consider system $P_i(s)$, and assume that, from station k, it is a single-input-single-output system. Then the residue of the j-th mode at control station k is a scalar defined by:

$$R_{kj}^i = \Omega_{kj}^i \Gamma_{jk}^i. \tag{8}$$

The residue is proportional to the sensitivity of the j-th mode to the controller gain. It is also called the functional sensitivity.

Applying a negative feedback control loop, at station k, of the form:

$$H_k(s) = \varepsilon h_k(s), \tag{9}$$

where ε is a scalar, and $h_k(s)$ has a given structure. The j-th eigenvalue will then be affected, and its shift, $\Delta \lambda_j$, is expressed by:

$$\Delta \lambda_j = -R^i_{kj}.H_k(\lambda_j).$$ (10)

If the eigenvalue λ_d is an open-loop critical mode, then its sensitivity with respect to the controller at station k is expressed by:

$$S_{\lambda_d} = \left| R^i_{kd} \right|,$$ (11)

which means that the eigenvalue shift is proportional to the magnitude of the residue.

3.2. Control signal effectiveness index

The residues change with the operating point. Assume that $H_k(s)$ can completely compensate the residue phase angle associated with the critical mode over the operating range. Then, only the magnitude of the residue plays a role in determining the effectiveness of the control signal. Hence, an index of effectiveness proportional to residue magnitude is used in [2]. But different types of input signals (power, voltage, speed, etc.) have significantly different base values. From (10) it is seen that by adjusting the gain of the controller, the same eigenvalue shift can be achieved using different input signals. Therefore, it is logical to use residue ratios instead of residues as an index for control signal effectiveness. Hence, the following index is proposed:

$$\rho_i = \frac{S^i_{\lambda_d}}{S^{i0}_{\lambda_d}} = \frac{\left| R^i_{kd} \right|}{\left| R^{i0}_{kd} \right|},$$ (12)

where λ_d is the critical mode, i defines the operating condition, k is the active control station, $\left| R^i_{kd} \right|$ is the magnitude of its residue, and $\left| R^{i0}_{kd} \right|$ is the residue magnitude for the nominal condition i_0.

If ρ_i, $i \in \Re$, remains constant for a set of operating points $\Re = \{1 \cdots m\}$, then it means that the corresponding signal is effective in the operating range $\Re$. On the other hand if the ratios change, then that signal is not effective for this range of operating conditions.

3.3. Index for effects of control signal on other modes

While the previous index can be used to assess the effectiveness of a control signal in shifting a given eigenvalue, the question that is now asked is whether other eigenvalues are affected by the same signal as well. The worst case is that the same signal will improve the damping of one mode and destabilizes other modes. The ideal case is when a signal affects the intended mode and leaves the other modes unchanged. The following index is proposed for this purpose:

$$SI^i_{\lambda j} = \frac{S^i_{\lambda j}}{S^i_{\lambda_d}} = \frac{\left| R^i_{kj} \right|}{\left| R^i_{kd} \right|}, \quad j \neq d.$$ (13)

This is the ratio of the sensitivity of other than the critical mode λ_j to that of the critical mode λ_d. It is independent of the coefficient of the input signals. The smaller the value of this index is, the lesser the effect of the control signal is on other than the critical mode.

3.4. Damping controller design

A dynamic compensator is needed in the case when static feedback control cannot provide adequate damping. The design of a dynamic compensator, as developed by the author [1], starts with residue phase compensation. To make the controller robust, different operating points should be considered, and the phase is compensated for at all of these operating conditions.

The least damped critical modes should be considered first. To achieve this compensation, a local controller at station k with the following transfer function may be used:

$$H_k(s) = k_k \frac{\tau_{wk}s}{1 + \tau_{wk}s} \prod_{j=1}^{m_k} \frac{1 + a_{kj}\tau_{kj}s}{1 + \tau_{kj}s}.$$ (14)

It consists of a gain, a washout stage needed when the impact of the controller on steady state is undesired, and m_k phase lead/lag stages. In each phase-lead/lag stage, a_{kj} is determined by the maximal compensation angle of this stage at a frequency ω_{kj}:

$$\phi_{kj}(\omega_{kj}) = \sin^{-1}\left(\frac{a_{kj}+1}{a_{kj}-1}\right),$$ (15)

where ω_{kj} can be either the imaginary part of a critical mode or a frequency where phase margin is needed. The time constant τ_{kj} is evaluated from

$$\tau_{kj} = 1/(\omega_{kj}\sqrt{a_{kj}}).$$ (16)

3.5. Case study

A two-area four-machine power system, shown in Fig. 3, is used as a case study for illustration. The power system has several control stations such as power system stabilizers installed at different machines, FACTS devices installed on transmission lines, etc. Here only one control station is to be designed, namely a Thyristor Controlled Series Compensation (TCSC) controller [10]. Two types of local measurements are available for use as control input signals. They are the local voltage magnitude y_1

and the tie-line active power flow y_2.

A damping controller is to be designed using either one of the two outputs as a control signal. The objective is to identify the most effective control signal among the two outputs. When the system is linearized at the nominal operating condition, it has a lightly damped oscillation mode $-0.01556\pm3.8515i$ which is 0.6 Hz inter-area oscillation mode.

Three operating conditions and the magnitudes of the residues corresponding to the inter-area oscillation mode are shown in Table 1.

From Table 1, the phase of the residue did not change much for the three operating conditions when y_1 is selected as the input signal. However, for the input signal y_2, the angle of the residue (87°) in case 3 has changed significantly from its values of (-84°) for case 1 or (-94°) for case 2. If the absolute value of y_2 is selected as the input signal, the residue phase in cases

Fig. 5. $SI_{\lambda i}$ vs. tie-line power flow.

1 and 2 will not change while in case 3 it becomes -93°. This makes the design of phase compensation controller much easier.

Fig. 4 shows the effectiveness index ρ_i for the two potential control signals when y_2 (power) changes from 1.5 pu to 4.5 pu.. In this range, it is seen that y_2 is much more effective compared to y_1.

Fig. 5 shows the interaction index $SI_{\lambda i}$ where λ_i corresponds to an oscillation mode other than the critical mode. It is seen that in this range using y_2 as a control signal, the controller will have less interaction with this mode λ_i.

Since both effectiveness index and interaction index suggest that y_2 is better than y_1, the damping controller is designed based on the absolute value of y_2 as an input signal. The angles of the residues of the critical mode are shown in Table 2. With lead-lag units as dynamic compensators, the root locus will leave the inter-are mode in the left half plane, thus the control will damp this mode.

The compensation phase is selected to be 90°. Two stages of lead-lag control are used, and with each providing a 45° phase compensation. The transfer function of the dynamic compensator is:
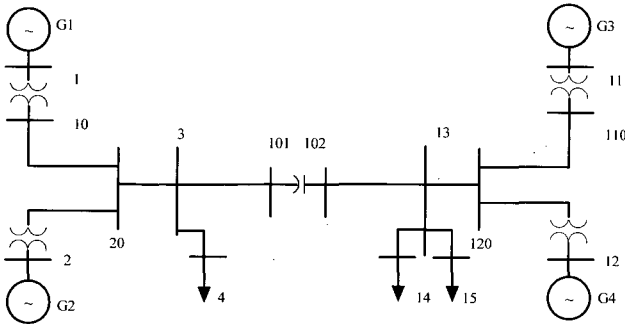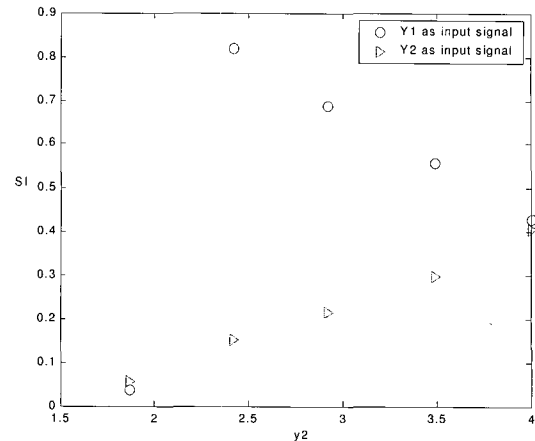

Fig. 3. One line diagram of a power system example.

Table 1. Magnitude and phase of the inter-area mode residues.

Case Number	Residue			
	Input: y_1		Input: y_2	
1	0.0113	74.12°	0.0938	-84.00°
2	0.0012	55.01°	0.0837	-94.04°
3	0.0155	66.41°	0.1496	87.16°

$$H(s) = 0.6\frac{3s}{1+3s}\frac{1+0.69s}{1+0.15s}\frac{1+0.69s}{1+0.15s}, \qquad (17)$$

where the gain is determined using the root locus diagram.

Fig. 6 shows the root loci of the system with the proposed controller at the three operating points. In all three cases, the inter-area mode will be well damped and the controller has little interaction with the other oscillation modes.

Fig. 4. ρ_i vs. tie-line power flow.

Table 2. Angles of residues.

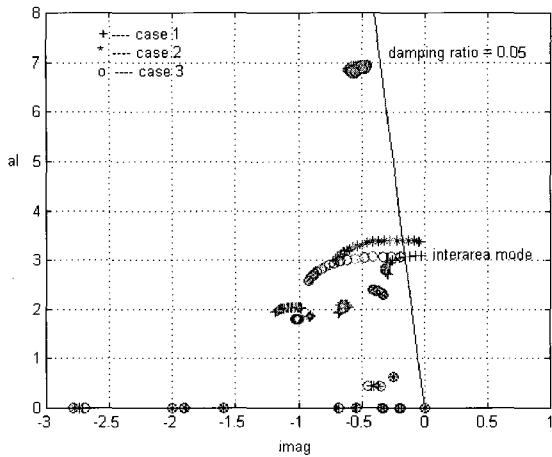| Case Number	Input signals $|y_2|$
1	-84°
2	-94°
3	-93°

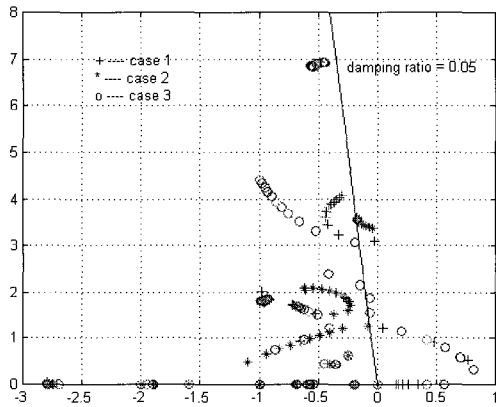Fig. 6. Root locus with absolute value of y_2, gain = 0 to 2, with a step of 0.1.

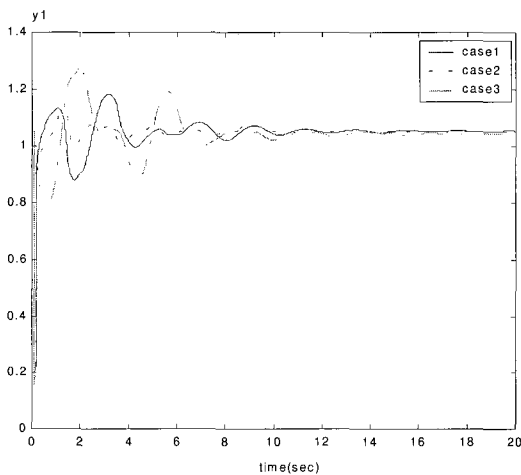Fig. 7. Root locus with y_1, gain = 0 to 1000, with a step of 100.

Fig. 8. Nonlinear simulation.

As a comparison, the controller using y_1 as input signal is also studied. The transfer function is:

$$H(s) = 100 \frac{s}{1+s} \frac{1+0.1s}{1+0.5s} \frac{1+0.1s}{1+0.5s} .$$ (18)

Fig. 7. shows the root loci of the system with the

controller of (18) at three operating points. For the nominal condition, the inter-area mode is well damped but for case # 2, it is not been damped well. The controller has quite an amount of interaction with the other oscillation modes.

A sample of the nonlinear simulation results, for y_1 as input,, is shown in Fig. 8 to illustrate that the controller improves the damping of the inter-area oscillations in all three cases. This figure shows the voltage magnitude y_1.

4. AUTOMATIC GENERATION CONTROL OR ENERGY BALANCING : DECENTRALIZED CONTROL STRUCTURE

4.1. Introduction and background

For many years electric utilities have used successfully a simple decentralized control structure in their automatic generation control scheme. This section builds on this success but it adds the effects of re-structuring, and aims to minimize wear and tear of the equipment, and also to satisfy the compliance criteria that are imposed by NERC, the North American Electric Reliability Council. Restructuring of the electricity industry has forced vertically integrated utilities that own generation, transmission, and distribution systems to split into independent and more specialized companies, including generation (Gencos), transmission (Transcos) and distribution (Discos) companies [3]. New participants have emerged to compete in the generation business and to provide ancillary services such as regulation and load following. To benefit fully from this environment, market participants have to minimize their operating and maintenance costs associated with generating units' maneuvering.

Specifically, regulation service, one of ancillary services provided by Gencos, is required to track fluctuations in Discos' power demand to provide continuous service to the customers, and also to comply with the performance standards imposed by NERC for equitable operation of an interconnected system. This service, energy balancing or regulation, is provided by the load frequency control mechanism (LFC), which is an automatic control of the generators' setpoints (also known as AGC: Automatic Genration Control). The LFC is to regulate a signal called ACE: Area Control Error. ACE accounts for errors in the interconnection frequency (ΔF) as well as errors in the interchange power with neighboring areas over tie lines, i.e. the tie-line power error (ΔP_{tie}). The ACE is given by:

$$ACE_i = \Delta P_{tie} - 10 B_i \Delta F ,$$ (19)

where (ΔF) is the interconnection frequency error and (ΔP_{tie}) is the tie-line power error. B_i represents a control area's frequency bias expressed in MW/0.1Hz.

Conventional LFC uses a feedback signal that is either based on the integral (I) of ACE or is based on ACE and its integral (proportional-integral or PI type controller). These feedback signals are used to maneuver the turbine governor setpoints of the generators so that the generated power follows the load fluctuations. However, continuously tracking load fluctuations definitely causes wear and tear on governor's equipment, shortens their lifetime, and thus requires replacing them, which can be very costly.

Here a novel load frequency controller is presented. It is manipulated by a fuzzy logic system whose rules are designed to reduce wear and tear of the equipment, and to assure its control performance is in compliance with NERC's control performance standards, CPS1 and CPS2. The LFC control structure is selected to be consistent with general practices and would be feasible for implementation. This control structure is a decentralized, integral-type controller whose parameter is automatically tuned using fuzzy rules. The control parameter is reduced to diminish high-frequency movement of the speed governor's equipment when the control area has high compliance with NERC's standards. When the compliance is low, the control parameter is raised to the normal value. The proposed methodology is assessed through a three-area power system including five Gencos and three Discos. To make the test system more realistic, both regulation and load following services are taken into account. Nonlinear simulation results that compare the proposed methods to conventional designs illustrate the effectiveness of the proposed scheme.

4.2. NERC's control performance standards

For equitable operation of the interconnected system, control areas have to comply with the North American Electric Reliability Council (NERC) control performance standards CPS1 and CPS2 which were adopted in February 1997. Each control area is required to monitor its control performance and report its compliance with CPS1 and CPS2 to NERC at the end of each month [4]. CPS1, CPS2 and the relationship between them are described next.

4.2.1 CPS1

CPS1 assesses the impact of ACE on frequency over a 12-month window or horizon. It is defined as follows: over a sliding 12-month period, the average of the "clock-minute averages" of a control area's ACE divided by "ten times its area frequency bias" times the corresponding "clock-minute averages of the interconnection frequency error" shall be less than the square of a given constant, ε_1, representing a target frequency bound. This is expressed by:

$$AVG_{12-month}\left[\left(\frac{ACE_i}{-10B_i}\right)_1 * \Delta F_1\right] \le \varepsilon_1^2, \tag{20}$$

where

ΔF :   interconnection frequency error,
B_i :   frequency bias of the ith control area,
ε_1 :   targeted frequency bound for CPS1,

$\left(\ \right)_1$:   clock-1-minute average.

To calculate CPS1, a compliance factor (CF) and a 1-minute average compliance factor (CF_1) are introduced:

$$CF = AVG_{12-month}\left[CF_1\right], \tag{21}$$

$$CF_1 = \left[\left(\frac{ACE}{-10B}\right)_1 * \left(\frac{\Delta F}{\varepsilon_1^2}\right)_1\right]. \tag{22}$$

CPS1 is then obtained from (23):

$$CPS1 = (2 - CF) * 100\%. \tag{23}$$

To comply with NERC, CPS1 should not be less than 100%.

4.2.2 CPS2

The second performance standard, CPS2, limits the magnitude of short term ACE values. It requires the 10-minute averages of a control area's ACE be less than a constant (L_{10}) given in (24).

$$AVG_{10-minute}(ACE_i) \le L_{10}, \tag{24}$$

where

$$L_{10} = 1.65\varepsilon_{10}\sqrt{(-10B_i)(-10B_s)}. \tag{25}$$

Note that B_s is the summation of the frequency bias settings of all control areas in the considered interconnection, and ε_{10} is the targeted frequency bound for CPS2.

To comply with this standard, each control area must have its compliance no less than 90%. A compliance percentage is calculated from the following equation:

$$CPS2 = \left[1 - \frac{Violations_{month}}{Total\ periods - Unavailable\ periods}\right] * 100, \tag{26}$$

where $Violations_{month}$ are a count of the number of periods that the clock-10-minute averages of ACE are greater than L_{10} in one month.

4.2.3 Relationship between CPS1 and CPS2

Gross and Lee [5] have shown that when CPS1 is met, CPS2 is automatically satisfied if:
1. ACE of each control area are independent random variables; and
2. The averages of these random variables are zero.

These conditions are assumed to hold in this paper and the fuzzy rules are designed to comply with CPS1 only. This reduces the complexity of fuzzy rule design.

and helps the actions of fuzzy rule based load frequency control to be even less complicated.

4.3. Fuzzy logic design

In this section, fuzzy logic rules are designed to manipulate the conventional integral-type load frequency control to achieve two objectives: (i) minimize equipments' wear and tear and (ii) comply with NERC's CPS1 and CPS2. The control structure for each area is of the form:

$$u = \Delta P_c = \alpha K_I \int ACE \, dt \,, \qquad (27)$$

where (ΔP_c) is the governor setpoint or raise/lower signal, K_I is the integral-control parameter and α is set using fuzzy logic and called fuzzy gain.

This paper uses only information that reflects compliance with CPS1 as the inputs to the fuzzy logic rules since CPS2 is assumed to be satisfied when CPS1 is met [5]. The proposed fuzzy logic will lower the control parameter when the control area has high compliance. On the other hand, that control parameter will be increased when the compliance with CPS1 of the control area is low.

This algorithm will significantly reduce wear and tear of unit equipment since movements of the governor setpoint or raise/lower signal (ΔP_c) generated from the integral controller are less frequent when the control area has high compliance or that values of 1-minute average compliance factor (CF_1) or accumulatively average compliance factor (CF_{ac}) is less than unity. CF_{ac} is defined below.

4.3.1 Input and output membership functions

The fuzzy logic system is developed based on Mamdani's method [6]. The inputs for this fuzzy system are the 1-minute average compliance factor (CF_1) and accumulative average compliance factor (CF_{ac}), defined in (22) and (28) respectively.

$$CF_{ac} = AVG_{X \to Y}[CF_1] \qquad (28)$$

$$CF = AVG_{X \to Z}[CF_1] \qquad (29)$$

In Fig. 9, point Y represents the current time where CF_{ac} is calculated every "one minute". Point Z represents the end of the twelve-sliding-month period where each control area is required to report its level of compliance to NERC. The output of the fuzzy system is the fuzzy gain α.

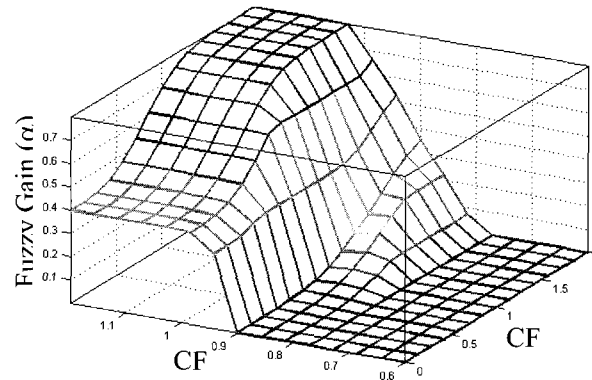Fig. 9. Twelve-sliding month time line for calculating compliance factors.
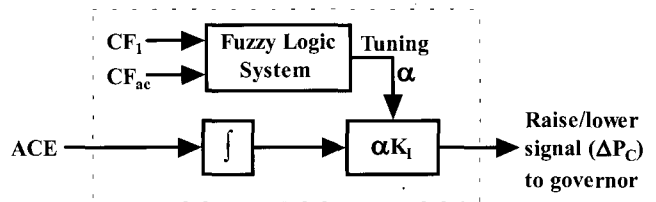

Fig. 10. Relationship of fuzzy system inputs and output.

Fig. 11. Fuzzy rule-based load frequency control.

4.3.2 Fuzzy rule design

Once the inputs are determined, the output, fuzzy gain, can be obtained. Fig. 10 describes relationship of the inputs and output of the fuzzy system through a 3-D mesh surface.

In the fuzzy rule-based load frequency control, the structure of the LFC is modified as shown in Fig. 11.

4.4. Test system

The effectiveness of the proposed fuzzy rule based load frequency control is demonstrated on a three-control-area power system, shown in Fig. 12. The test system includes five Gencos and three Discos. Area (1)
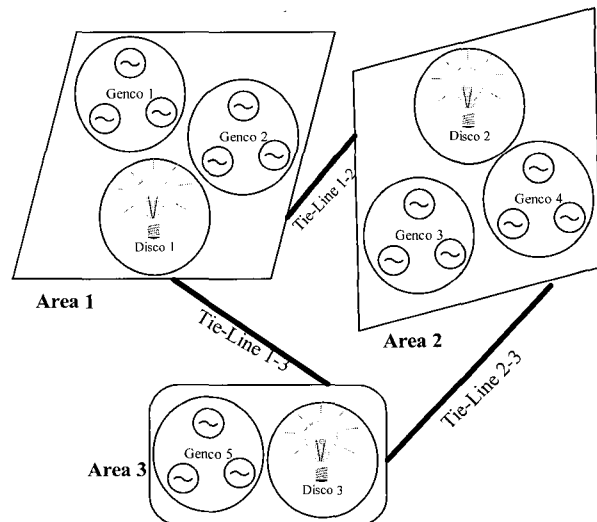

Fig. 12. A three-area interconnected power system.

and Area (2) each has two Gencos and one Disco, and Area (3) has only one Genco and one Disco.

In order to satisfy customers' power demand and to comply with NERC's standards, Discos call for load following and regulation services from Gencos providing ancillary services. After their bids and offers are matched, those services are provided by Gencos according to established contracts [7,8].

4.4.1 Load following contracts

The generating units, which provide load following services, will ramp their generation to follow slow load fluctuations, which can be forecast from time of day, day of week, weather, etc. In the test system, these services are taken into account. The contracts are given in Table 3.

The cell (i,j) in Table 3 shows the percentage of load following requirement (MW) from Disco (j) provided by Genco (i).

Table 3. Load following contracts.

	DISCO1	DISCO2	DISCO3
GENCO1	80%	20%	-
GENCO2	-	-	-
GENCO3	-	50%	-
GENCO4	-	-	-
GENCO5	20%	30%	100%

Table 4. Regulation contracts.

	ACE1	ACE2	ACE3
GENCO1	-	-	-
GENCO2	100%	-	-
GENCO3	-	50%	-
GENCO4	-	50%	-
GENCO5	-	-	100%

4.4.2 Regulation contracts

Fast fluctuations in aggregate load, which can be described as a form of random movements, cannot be matched by load following services. Consequently, resultant mismatches represented as area control error (ACE) are taken care of by those units providing regulation services [9,11]. The contracts for these services are given in Table 4.

4.5. Simulation

The proposed technique is applied to the test system under a load pick-up hour scenario. Fig. 13 shows the load changes, which consist of linear and random components. The linear components can be satisfied by load following services and the random components will be met by regulation services.

In this section, the performance of fuzzy rule based load frequency control is assessed through nonlinear simulation under the assumption that all control areas are facing marginal compliance with CPS1, i.e., their current percentages of compliance with CPS1 are at 100%. Fig. 14 shows the plots of changes in governor setpoints or raise/lower signals (ΔP_c) of each generating unit. In addition, the raise/lower signals from a conventional LFC are plotted on the same graph for comparison.

The excess maneuvering of the conventional LFC scheme is better seen in Fig. 15, where the difference between both signals is plotted to show superior performance of the fuzzy rule based load frequency control. The latter reduces high frequency components. The fuzzy gains (α) used to tune the control parameters of LFC are automatically changed according to individual control areas' percentage of compliance with CPS1.
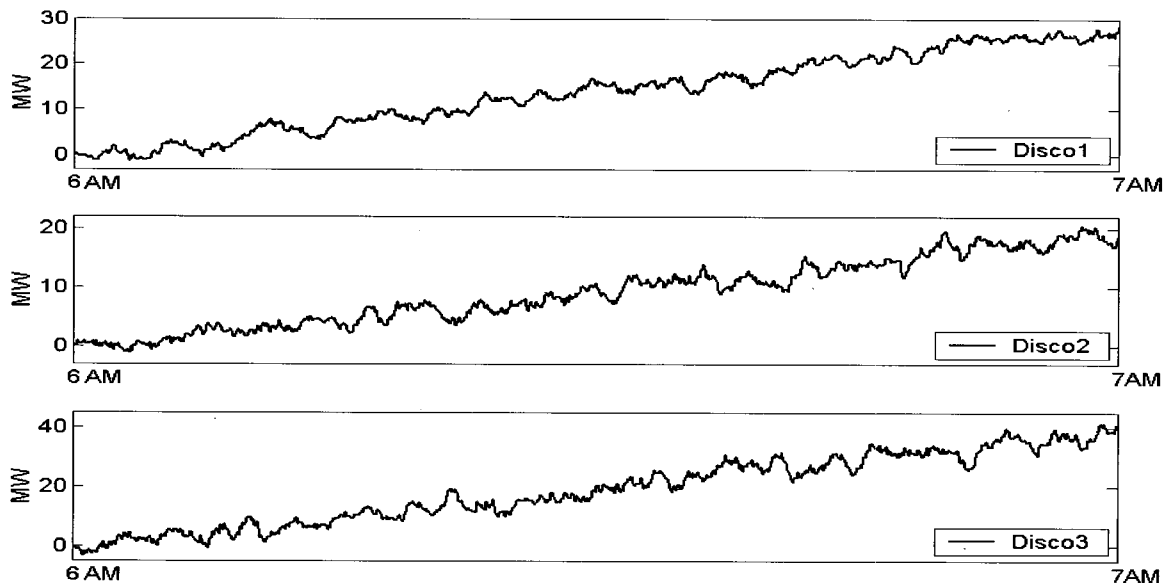

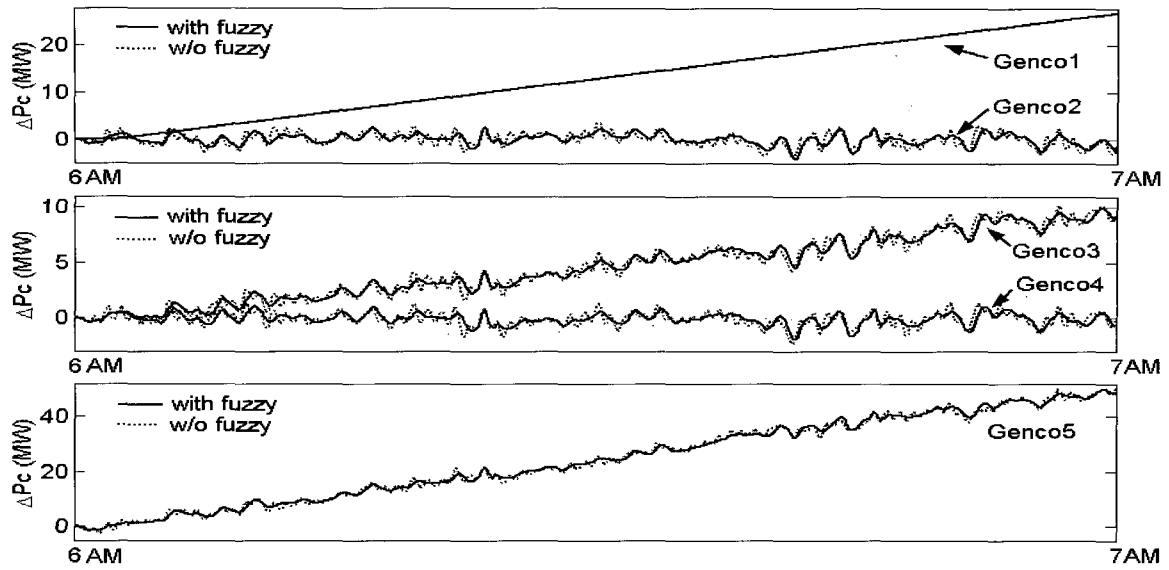Fig. 13. Aggregated load changes for each disco during load pick up hour.

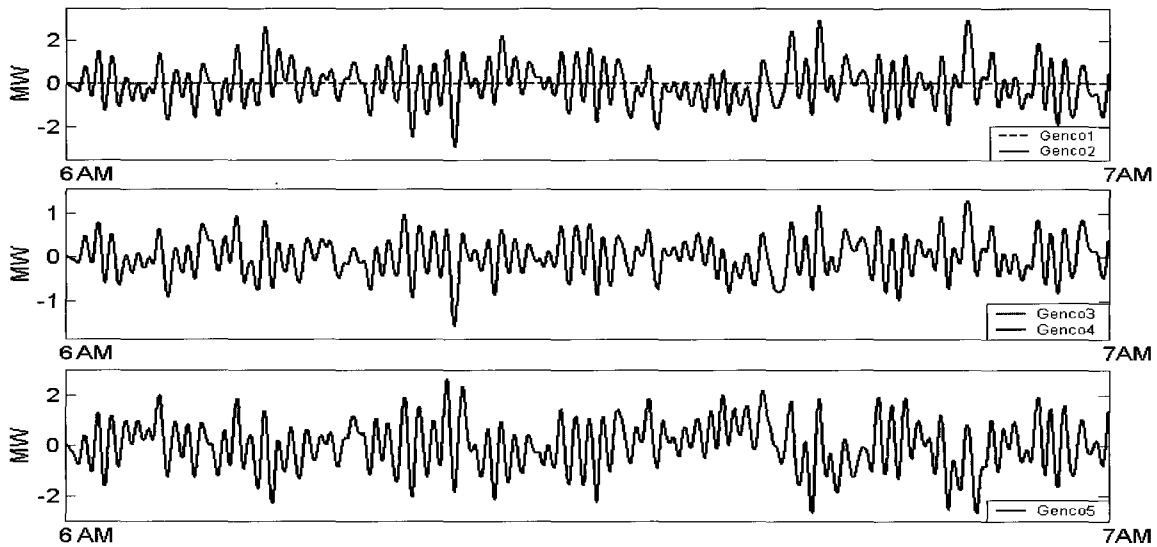Fig. 14. Raise/lower signal of each generating unit.

Fig. 15. Excess raise/lower signals of conventional LFC over proposed fuzzy based LFC.
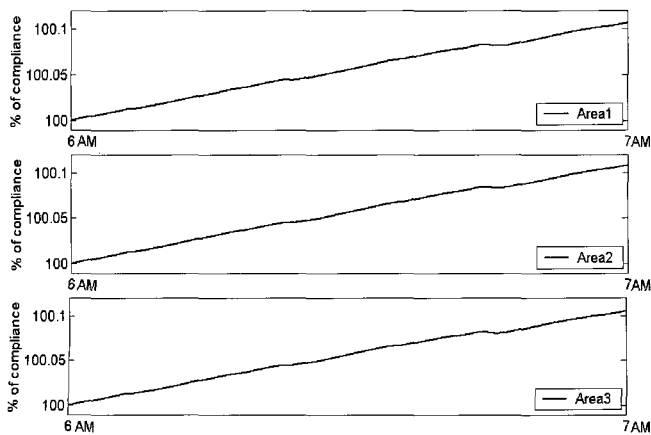

Fig. 16. Percentage of compliance with CPS1 for each control area.

Table 5. 10 Minute average of ACE compared with L_{10}.

	$AVG_{10}(ACE1)$	$AVG_{10}(ACE2)$	$AVG_{10}(ACE3)$
6:00-6:10	0.1410	0.4244	0.4636
6:10-6:20	0.3379	0.0322	0.0596
6:20-6:30	0.1551	0.1599	0.4811
6:30-6:40	1.6432	1.0359	0.0607
6:40-6:50	1.1763	1.0325	0.6505
6:50-7:00	1.0931	0.7466	1.2886
L_{10}	10.9711	10.5801	11.0019

The fuzzy rule LFC also assures compliance with NERC's control performance standards. To demonstrate this advantage, the percentage of

compliance with CPS1 of each control area is shown in Fig. 16.

The simulation results in Fig. 16 show that the percentages of compliance with CPS1 of all control areas are raised above 100%. In Table 5, the "10-minute averages" of ACE of control areas are calculated and compared with the constants (L_{10}). According to NERC's control performance standards, these averages of ACE must be equal or less than L_{10} at least 90% of the time to comply with CPS2. From the results, all 10-minute averages of ACE of each control area are less than its standard constant L_{10}, and these results are in compliance with CPS2.

5. RECOMMENDATIONS

The following two recommendations are presented in view of the business aspects of power systems and the need for an autonomous system.

5.1. On the economics of control

There is no doubt that control is a must for efficiently and reliably operating the power system. Controllers can be placed in various places and they belong to independent entities. Governor, excitation controls are at the turbogenerators which belong to generation companies (Gencos), FACTS devices might belong to the transmission companies (Transcos), responsive load controllers and protection apparatus could belong to the distribution companies (Discos), consumers and market players will have their own controls. Even for this simplified view, it is hard to tell who will be in charge of control. Who is going to be in charge of designing and coordinating these controllers? If more control devices are needed, who will determine this and how, and who will pay for them. Will there be a *Control Provider*? If there will be a control provider, then the control value added is to be assessed through price, risk and benefit analysis.

5.2. Vision

The vision that one might have for a power system is an autonomous system controlled by distributed intelligent agents. Coordination of distributed controllers is performed to obtain a global system control objective. The system has to be fault tolerant in order to be attractive. Local controllers need to be designed such that the system will still be functional in the event of the failure of a local controller. The multiplayer and multiobjective system consists of at least three layers: (i) an electrical network, (ii) a computer and communication network, and (iii) a business and economics layer. To make this critical infrastructure operational and efficient, power system operators and planners will have to develop tools and methodologies that combine information technology,

principles of business and economics, and power system engineering. A common software platform to simulate all aspects of power systems dynamics and economics is needed. The specific challenges are the design of intelligent agents for energy management and robust control of power system dynamics, development of analytic tools to evaluate the value added of those controllers, evaluation of existing and proposed market structures in providing efficient incentives for implementation of robust controllers, and proposed modifications that will provide different incentives to encourage more efficient decisions about hardware and software modifications to the grid. Challenges will involve defining agents, their information requirements, their architecture, and their internal intelligence. Re-enforcement learning for example could provide an answer.

6. CONCLUSION

The paper describes some of the challenges that face the control of nonlinear interconnected power systems. The challenges include the selection of appropriate control and information structures that could range from a completely decentralized to a fully centralized structure. Once a structure is proven to be feasible, the effectiveness of control signals needs to be assessed. Analytical tools are derived for this purpose in the first part of the paper, and they are illustrated with a case study that involves the design of a damping decentralized controller using a Thyristor Controlled Series Compensation device. The second part of the paper deals with the load following and tracking problem through automatic generation control for a system that has been re-structured or deregulated. This problem can be solved using a completely decentralized scheme. It is solved here using fuzzy rules and with an emphasis on compliance with NERC's standards and reduction of wear and tear of the equipment. It is illustrated with a test system that has three interconnected control areas. The test system includes five Gencos and three Discos. Area (1) and Area (2) each has two Gencos and one Disco, and Area (3) has only one Genco and one Disco. The paper addressed mainly stability enhancement thru damping control design and energy balancing issues. There are several other challenging control aspects that face the power system control designer, including voltage control, load control, control of distributed resources, etc. The paper presents also comments on the economics of control and the author's vision on autonomous systems.

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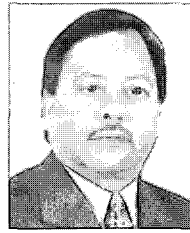
Ali Feliachi received the *Diplôme d'Ingénieur en Electrotechnique* from Ecole Nationale Poly-technique of Algiers in 1976, and MS (1979) and PhD (1983) in Electrical Engineering from Georgia Institute of Technology, Atlanta, GA. He joined West Virginia University (WVU) in 1984 where he is now a Full Professor, the holder of the endowed Electric Power Systems Chair position in the Lane Department of Computer Science & Electrical Engineering, and the Director of the Advanced Power & Electricity Research Center at WVU. He has been working in the field of large scale systems with emphasis on electric power systems for more than 25 years, and he has over 200 publications. Dr. Feliachi is a senior member of IEEE, and a member of Pi Mu Epsilon, Eta Kappa Nu, and Sigma Xi. He received an ASEE Dow Outstanding Young Faculty Award in 1987, and the following awards from the College of Engineering & Mineral Resources at WVU: Leadership (1989), Research (1991, 2004, 2005), Researcher of the Year (2005), Graduate Teacher (1991). In 1994 he received the Claude Benedum Distinguished Scholar Award for the Sciences and Technology from WVU.