4) The 10-minute, or even longer, average of ***ACE*** in one control area is independent of the same in another control area.

We continue to believe our data analysis reported in [6] and, hence, we see no basis on which any of these assumptions could stand.

In setting target frequency for the above interconnections in Section 3.6, pp. 3-15 to 3-18, we realized that we could provide US control areas with the opportunity of saving hundreds of millions of dollars annually if we provided the highest allowance on the RMS of ***ACE*** several minute average. The larger the allowance, the lesser need for a control area to track load fluctuations, as the fluctuations would be served by the interconnection. This in turn would reduce the need for unit maneuvering in the control area. For realizing the same frequency, however, the highest allowance can be provided if the interconnection can be assured of independence among ***ACE***s. By realizing an ***ACE*** that has no dependency on time of day a control area can make its ***ACE*** independent of other ***ACE***s. An ***ACE*** whose several-minute averages is random, i.e., has negligible auto-correlation in all orders beyond several minutes, could have only a negligible dependency on time of day.

Whenever the dependency of ***ACE***s on time of day becomes negligible, the RMS of T clock-minute frequency error average will decay at a much higher rate than has been experienced. On this basis, we recommended the curves presented in Fig. 3.8, page 3-17, as the target frequency for the Eastern and ERCOT interconnections. They allow a much larger target for clock-minute frequency error average than was being experienced, but provide a somewhat tighter target for longer-term frequency error averages.

We believed, and continue to believe, that at least two points on each of the recommended curves should be used as interconnection LFC performance standards. We recommended one point at 60 min so that audited MWh data, instead of MW data, could be used for measuring each control area's performance. The other point could be in the range of 1 to a dozen minutes.

Some members of PS did not want any CPS to include the effects of metering and other errors inherent in interconnected operation. On this basis, these members rejected the use of audited MWh data in measuring control area performance. Some others, who had concerns about increased unscheduled power flow over their ties, adamantly advocated a CPS that explicitly requires limiting several minute averages of ***ACE***.

Under the above constraints, we recommended that NERC adopt a CPS which would measure the expected value of 10-minute average ***ACE*** times 10-minute average of frequency error. To break the impasse, however, we seized the opportunity and supported CPS_1 and CPS_2. The target for 1-minute frequency average error in CPS_1 is even somewhat larger than the target we had sought. Further, we computed the limit applied on 10-minute average ***ACE*** on the basis of avoiding any additional constraint on a control area whose ***ACE*** is independent of others. Therefore, the resulting L_{10} for all control areas became significantly larger than L_d, the limit imposed by the old A_2, and for most control areas L_{10} became two to four times of L_d. The NERC adoption of CPS_1 and CPS_2 accomplished one major objective we had, that was to provide the power industry with the opportunity of increasing its benefits from interconnected operation by hundreds of millions of dollars annually.

As indicated in Section 7.4.1 pp. 7-4 and 7-5, we believed compliance with CPS_1 and CPS_2 alone would not maintain frequency statistics at the experienced levels. The analysis performed on the frequency realized under CPS_1 and CPS_2 by various members of PS has since verified our concerns. The remedy is not to lower ε_1 by a large percentage or tightening L_{10}. If further deterioration in frequency cannot be tolerated then a CPS, as proposed in [6] and [7], that measures expected value of the product of hourly averages of ***ACE*** and frequency error should be enacted. In such a case, audited MWh data, instead of MW data, should, of course, be used.

Many control areas had a CPS_1 score higher than 180% in all the NERC CPS compliance reports we monitored during 1998 to 2000. Even among control areas that did not much overachieve CPS_2 it was rare to find one with a CPS_1 score of less than 150%. On this basis, as we expected, CPS_1 has no influence on the realized frequency. It is compliance with CPS_2, other non-CPS related NERC requirements, and continued traditional control practices by many control areas that has maintained frequency at the current experience. Without CPS_2, the RMS of all averages of frequency error could grow even further and, hence, we do not support the paper's main conclusion that "CPS_2 criterion provides no additional insight in terms of control performance and the monitoring of CPS_1 suffices."

The authors have analyzed data from different interconnections to construct Table I in the paper. We believe that if they compute RMS for 1 and 10-minute frequency error average, the former will be considerably lower than ε_1, while the latter will be about or higher than ε_{10}. If so, would this finding not go against the assumptions and the above conclusion made in the paper?

The objective of Tie Line Bias Priority-based Control presented in Section VI is to realize, with minimum unit maneuvering, an ***ACE*** that is independent of ***ACE***s in other control areas. We set L_{10} at a value that imposes no additional restriction on control areas whose ***ACE*** is independent of others. If ever control practices make ***ACE***s sufficiently independent of each other, then, as said in the third paragraph of page 6-6, continued imposition (or removal) of CPS_2 would not be an issue.

Publication of this paper encouraged us to reiterate our findings and share the constraints and incentives that led to the adoption of CPS_1 and CPS_2. We wish the authors well in all their endeavors.

Closure of "Analysis of Load Frequency Control Performance Assessment Criteria"

George Gross and Jeong W. Lee

George Gross and Jeong Woo Lee [University of Illinois at Urbana-Champaign]: We welcome the comments and questions of Jaleeli and VanSlyck and appreciate their interest in our work. We begin our response by reiterating the importance with which we view the pioneering work of the discussers [6], [7] and the key role this work played in the research reported in this paper. At the outset, we also need to emphasize that the aim of our paper was to provide a firm analytical basis for the formulation, analysis, and evaluation of load frequency control (LFC) performance criteria. We constructed a solid analytical basis by effectively exploiting the concepts of random processes and probabilistic models to develop the general criteria for LFC performance. The general LFC criterion we formulated using our analytical framework has as special cases the NERC ***CPS1*** and ***CPS2*** criteria. As a

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byproduct of our analysis, we found a redundant relationship between the two criteria under the conditions stated in the paper. As such, the similarities mentioned in the discussion should not in any way be surprising.

The discussion presented has, by and large, an implementation orientation. We appreciate the review of the work in [6] and, in particular, the emphasis on the practical considerations and multiple constraints that clearly must be taken into account in the implementation of LFC criteria. We recognize the importance of these aspects of the work even though they were not within the scope of the work we reported on. Rather, our objective was the construction of a general framework to permit the assessment of key issues associated with metrics for LFC performance. We aimed to provide a basis for the analysis of the LFC performance criteria.

The tone of the discussers' comments, however, leads us to infer that, in many ways, both our objective and the nature of our results were misinterpreted. As we concluded in the paper, we developed the framework "to bring considerable new analytic insights into the LFC performance assessment problem." This very general framework provides a basis for the formulation of LFC criteria and serves well for the analysis of the measurement requirements for LFC. Consequently, our paper should be judged in that context.

We next turn to responding to the specific questions raised by the discussers. These questions are concerned with the assumptions introduced in constructing the analytical framework. The first three questions are focused on the rationale for the assumption that the collection $\{\boldsymbol{F}(t_\ell)\colon\ \ell = 0, 1, 2, \ldots\}$ constitutes a set of independent and identically distributed random variables (r.v.s). The first question asks the basis for the assumption that the probability distribution of the frequency error and that of ACE are independent of time. We do not make such an assumption in our framework. In fact, we carefully heeded the warnings and statements in [6] "that current practice and the AGC coding logic presently used by many control areas yields a frequency error that is "dependent" on time." It was precisely the fact that the frequency error is time dependent that motivated us to apply the concepts of stochastic processes. Such processes are inherently time dependent and consequently no assumptions of time independence are made. We explain briefly why the discussers may have interpreted otherwise.

Let $f(t)$ denote the *measured* frequency error. This is one *sample path* of the random process $\boldsymbol{F}(t)$. The random process $\boldsymbol{F}(t)$ is clearly time-dependent and so is the sample path. In our framework, we do introduce the assumption of the probability distribution of each r.v. $\boldsymbol{F}(t')$ for an arbitrary time instant t' is independent of the value of t' selected. In other words, the probability distribution of the r.v. $\boldsymbol{F}(t')$ is the same as that of $\boldsymbol{F}(t'')$, where t'' is some other time instant, $t'' \neq t'$. Therefore, we assume that the probability of each r.v. of the stochastic process $\{\boldsymbol{F}(t_\ell)\colon\ \ell = 0, 1, 2, \ldots\}$ is independent of time. Of course, the distribution depends on many random factors, such as weather and consumer behavior, whose outcomes are uncertain. The model suppresses these random factors since the only uncertainty is that of the frequency r.v. at each instant of time. However, no loss of generality is incurred by assuming that these random factors can have the same impacts at any instant of time and so are considered to be not time-dependent. It is precisely this rationalization that led us to assume that $\{\boldsymbol{F}(t_\ell)\colon\ \ell = 0, 1, 2, \ldots\}$ is a collection of r.v.s with identical distributions. Moreover, we view the r.v.s in this collection to be independent since the r.v. at t' has no effect on the r.v. at t'', $t'' \neq t'$. Thus, we have a collection $\{\boldsymbol{F}(t_\ell)\colon\ \ell = 0, 1, 2, \ldots\}$ of independent and identically distributed r.v.s.

All of the statements that describe the stochastic process $\boldsymbol{F}(t)$ are equally applicable to the stochastic process $\boldsymbol{ACE}(t)$.

The second question is concerned with the basis for the assumption that the state of the frequency and $\boldsymbol{ACE}$ r.v.s "in one instant has no effect on the state at any other instant." The response to the first question addressed, in effect, this question, as well. Furthermore, the sole relationship between $\boldsymbol{ACE}$ and the other variables is the defining equation

$$\boldsymbol{ACE}_i(\boldsymbol{t}) = \boldsymbol{T}_i(\boldsymbol{t}) - 10B_i \cdot \boldsymbol{F}(\boldsymbol{t}).$$

This relationship clearly states that $\boldsymbol{ACE}_i(t)$ is related to $\boldsymbol{T}_i(t)$ and $\boldsymbol{F}(t)$ with all variables being observed at the same instant t. There is no other relationship in terms of time that is given. In terms of the discussion on the stochastic process $\{\boldsymbol{F}(t_\ell)\colon\ \ell = 0, 1, 2, \ldots\}$, the assumption that $\boldsymbol{ACE}_i(t')$ is independent of $\boldsymbol{ACE}_i(t'')$ with $t' \neq t''$ is perfectly reasonable.

The responses here to the first two questions provided the answer to the third question. This third question focused on why "a collection of samples of each of these variables is a set of independent and identically distributed random variables."

The fourth question of the discussers focused on the independence of the 10-minute, or even longer, average of $\boldsymbol{ACE}$ in one control area of that of another control area. It is appropriate to consider the operations in one control area as reasonably independent of those of another area due to the characteristics of the load and the nature of the generation resources of each control area. Moreover, the work of the discussers indicates that $\overline{\boldsymbol{ACE}_i}(t)$ and $\overline{\boldsymbol{ACE}_j}(t)$ are weakly correlated [6]. We can interpret "weakly correlated" as approximately "uncorrelated." We used the *Central Limit Theorem*, to show that for each control area i, $\overline{\boldsymbol{ACE}_i}(t)$ is approximately normally distributed. Since two normally distributed r.v.s are independent if and only if they are uncorrelated, it follows that the weakly correlated $\overline{\boldsymbol{ACE}_i}(t)$ and $\overline{\boldsymbol{ACE}_j}(t)$ can be considered to be independent.

In summary, the assumptions introduced are necessary for the construction of the analytical framework for our work. We relied heavily on the body of data provided in [6] to justify their reasonableness.

We thank the discussers for their detailed comments. These comments provided good insight on the implementational aspects of the LFC criteria which will be useful for future work in the area.