AUTOMATIC GENERATION CONTROL ANALYSIS WITH GOVERNOR DEADBAND EFFECTS

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Abstract - Automatic Generation Control (AGC) stochastic performance, including effects of speed governor deadbands, is analyzed. Using Fast Fourier Transform techniques, Bonneville Power Administration real system data is compared with similar data from simulation.

Analysis of the real system data indicated a high correlation between system frequency and Area Control Error throughout the 0.5-15 cycle per minute spectrum of interest. However, well defined limit cycle frequencies due to governor deadbands are not detected. Comparison of simulation results with system data indicates that deadband effects may be small or negligible in the AGC process. Simulation results show that there is little value in varying AGC frequency bias coefficients with disturbance size, but that unnecessary control action can be reduced by varying the bias coefficients with system loading.

INTRODUCTION

During normal operating conditions, Automatic Generation Control (AGC) is characterized by random variation of loads in each control area. AGC matches area generation to area load plus scheduled net interchange by controlling generation to maintain the net interchange schedule and scheduled power system frequency. For normal operating conditions, it is important to minimize unnecessary control action. The frequency spectrum of interest is from below 1 cycle per minute (CPM) to about 10 CPM. The lower frequencies are associated with random load changes colored by AGC, while the higher frequencies are associated with random load changes colored by the primary speed governor control.

Control action is conventionally based on the Area Control Error computation (ACE = ΔP_{TL}-BΔf). A time deviation term is added in the western North American interconnected system. Present industry practice[1] is to set the frequency bias coefficient, B, approximately equal to the "natural" system frequency characteristic, β, during heavy load conditions. The natural characteristic is measured for large disturbances, with bias coefficients normally changed only at the start of a new calendar year.

Area control action has been described as based on the integral of ACE with ACE integraton obtained from the governor speed reference motors. This is somewhat oversimplified, however, due to the ACE time deviation term, intentional and unintentional non-linearities, integral or derivative control terms in probability filters or plant AGC controllers,[2,3,4] and intermediate feedback of unit or plant output power to ACE allocation algorithms[3,5] or plant AGC controllers.[4] The probability filter used by BPA has evolved from the original design by Ross[2] and is very effective in minimizing unnecessary control action. The principle unintentional non-linearity is deadbands of the hysteresis or backlash type located in various governor valves or linkages.

The effect of governor deadbands (backlash) on AGC has been of interest for some time.[6,8,12] One effect may be to reduce β for small disturbances. Based on system observation and simulation, Ewart analyzed the effect of governor deadbands on the ACE frequency bias coefficient for different system loading and disturbance sizes.[8] He hypothesized that governor deadbands may cause AGC system limiting cycling with periods of 30 to 90 seconds.

Preliminary simulation results indicated that setting B higher than β (corresponding to light system loading and/or small disturbances) resulted in considerable unnecessary control action. These results, along with Ewart's analysis, led to analysis of AGC normal operating condition data and development of improved simulation models. Deadbands were included within aggregate governor turbine models of hydroplants (consisting of numerous, often identical, units) and of generation equivalents for interconnected areas. These models were implemented in the Bonneville Power Administration AGC simulation program[3] which employs the average frequency concept usually appropriate for the low frequencies associated with AGC. Stochastic simulation results were then compared with real system AGC performance during normal operating conditions.

ANALYSIS OF SYSTEM AGC DATA

Power system frequency, net tie-line power deviation, and area control error (ACE) were recorded digitally at BPA's Dittmer Control Center. Analysis consisted of statistical tests for stationarity, and computation of probability density estimates, cross power spectral density estimates, and coherence functions.

The following data for heavy and light loads were recorded:

1. Tuesday, August 2, 1977; 1010-1225 hours (relatively heavy load)
   Record length = 8,100 seconds = 135 minutes
   RMS Values: Δf = 0.0141 Hz, ACE = 28.2 MW, ΔP_{TIE}=49.5 MW
2. Saturday, August 6, 1977; 0101-0401 hours (light load)
   Record length = 10,800 seconds = 180 minutes
   RMS values: Δf = 0.008 Hz, ACE = 25.8 MW, ΔP_{TIE}=23.5 MW

The system frequency deviation measurement resolution is one millihertz. Frequency deviation is computed digitally at 0.1 second intervals and then converted

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to analog form. The analog signal is passed through a first order lag with 0.3 second time constant. For the analysis, the AGC data were sampled and recorded at 2 second intervals.

During the August 2nd recording, 1100 MW of generation was dropped in an external control area. This is reflected in the RMS values given. BPA area frequency characteristic, computed digitally 10-40 seconds following the disturbance, varied from 182 to 298 MW per 0.1 Hz. The AGC bias value used during 1977 was 220 MW per 0.1 Hz. System spinning capacity, assuming the nominal 5% governor droop settings, indicated a system characteristic of approximately 370 MW per 0.1 Hz.

Stationarity Test and Probability Density Functions

The run test[9] was performed to test the stationarity of the frequency deviation data records. Data during large disturbances were first removed. The procedure then was to divide the data into N equal times intervals with the data in each interval considered independent. The standard deviation for each interval was then computed and tested for the presence of underlying trends or variations other than those due to expected sampling variations.

Since the test showed that the frequency was not stationary at the 5% level of confidence a second-order trend remover was developed. With trend removal, stationarity was improved but still did not pass the run test at the 5% confidence level. Weak stationarity was assumed, however, but the results should be used with caution. Figure 1 shows the probability density function of the frequency before and after the trend was removed, for August 6 data. The sharp peak at zero frequency deviation in this figure is due to a frequency measurement equipment aberation. After removing the trends, the probability density functions of frequency deviation were roughly Gaussian.

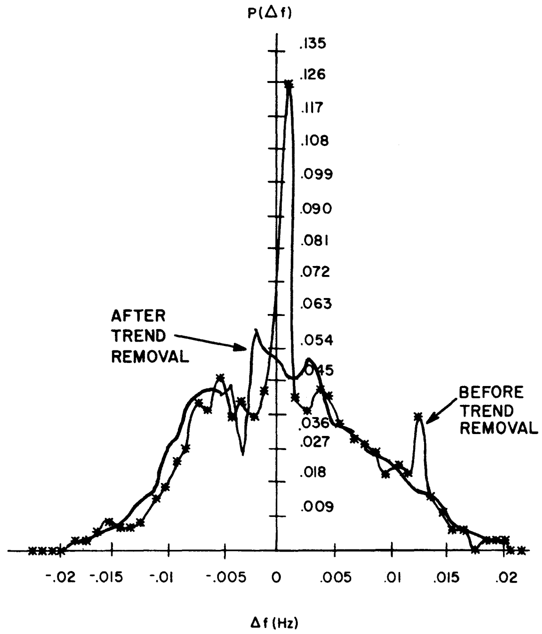

Fig. 1. Probability density function of system frequency deviation for August 6, 1977 data. Sharp peak at 0.001 Hz is due to instrumentation defect. (* is before trend removal, and heavy line is after trend removal).

Power Spectral Density Estimates

Power spectral density estimates were computed in the 0.5-15 cycle per minute (CPM) range using the Fast Fourier Transform. Analysis of frequency below 0.5 CPM would require very long data records which would be highly nonstationary. A 512 point transform corresponding to 1024 seconds of data was used, which corresponds to 256 spectral lines at 60/1024 = 0.059 CPM intervals. A double Hanning data window was used.

The records were broken up into 1024 seconds segments with 50% overlapping of segments. The overlapping recovers about 90% of the data lost due to the windowing. The power spectral density estimates for the individual segments were then averaged, spectral line by spectral line, to reduce variability. The variability is reduced inversely as the square root of the number of segments averaged. Twelve segments were averaged for August 2 data and 18 segments were averaged for the August 6 data.

The power spectral density estimates of frequency deviation showed fairly smooth decay from 0.5 to 6 CPM for both data records (Figure 2). Throughout the spectrum, densities are larger for the light load data. Well defined limit cycle frequencies were not evident.

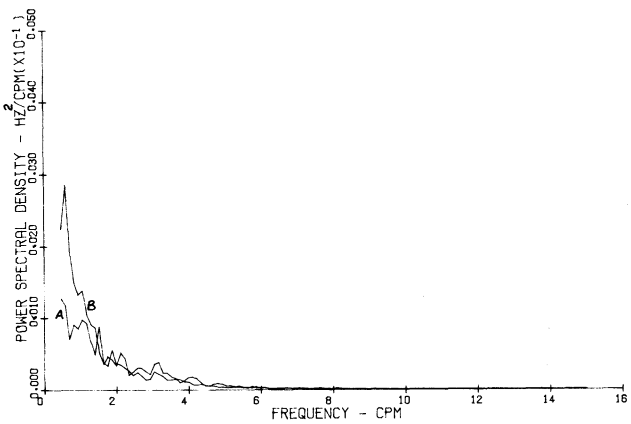

Fig. 2. Power spectral density functions of system frequency deviation for heavy load data (Curve A) and for light load data (Curve B).

Coherence Function of ACE and Frequency Deviation

Cross-spectral density estimates between ACE and system frequency deviation were computed using the Fast Fourier Transform. Correlation at each frequency was determined by computing the coherence function from the cross-spectral density function of the two variables and the power spectral density functions of each variable (Figure 3). A coherence function value of one means the variables are fully coherent or correleated at a particular frequency while a value of zero means the variables are incoherent or uncorrelated.

Figure 3 indicates high correlation between ACE and system frequency deviation at most frequencies. This may be surprising since, as discussed by Ewart,[8] ACE and system frequency deviation supposedly measure two different things (ACE measures area generation-load unbalances while frequency deviation reflects the entire power system generation-load unbalance). The high correlation at the lower frequencies is in agreement with observations on the Eastern North American interconnection. It was expected that correlation would be higher during the light load period when AGC frequency bias may be considerably greater than the natural system characteristic for small disturbances. However, a large difference in correlation between heavy and light load is not evident.

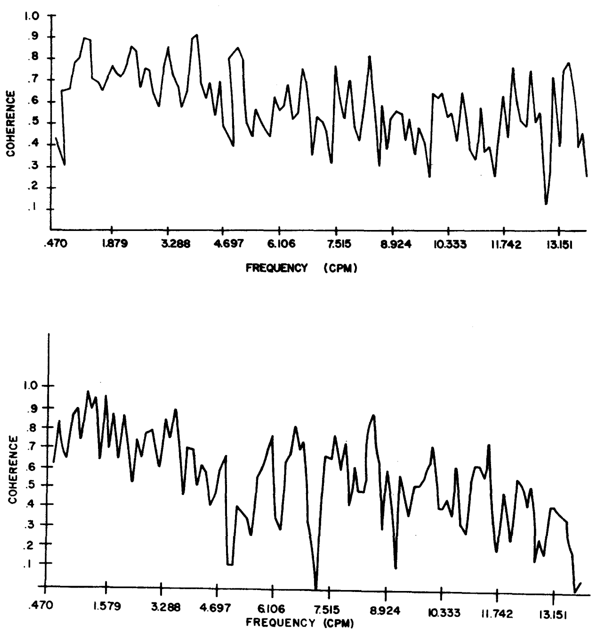

Fig. 3. Coherence functions of ACE and system frequency deviation for heavy load data (top) and for light load data (bottom).

GOVERNOR DEADBAND MODEL

The Joint AIEE-ASME Standards for steam and hydraulic turbines define deadband as "the total magnitude of a sustained speed change within which there is no resulting measurable change in the position of the governor-controlled valves (or gates)."[10,11] Deadband is expressed in per cent of rated speed. The standards limit deadband widths to 0.06% (0.036 Hz) with recent hydro governor specifications requiring 0.02% (0.012 Hz) deadband. Deadbands have been essentially eliminated on the new Grand Coulee hydro governors.[7] Modern steam units may have deadbands less than 0.02%. The typical RMS value of western power system frequency fluctuations of about 0.008 Hz provides some indication of the overall systems effective deadband. It is possible that dither modulation effects (ref. 14, page 322) due to higher frequency oscillations of generator rotors may reduce effective deadband widths.

Figure 4 shows the method used to represent the composite effect of governor deadbands or backlash within aggregate governor-turbine models. As many as 10 discrete deadband models, each having different widths, were used for each generation equivalent. The location of the deadband models are the same as used in the EPRI Long Term Power System Dynamics Program.[15] The individual deadband widths follow a normal distribution determined from a random number generator. For the simulations described below, deadband widths with means of 0.0001 pu (0.006 Hz) with 3-sigma (3 standard deviations) values of 0.00005 p.u. were generally used.

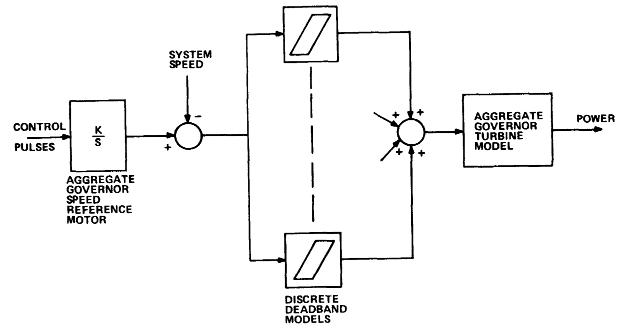

Fig. 4. Block diagram of aggregate governor-turbine model with discrete deadbands.

Although the deadband modeling is computationally inefficient, it provides a simple and straightforward means to evaluate the effects of deadbands on the AGC process. An aggregate deadband model was also developed which consisted basically of a nonlinear governor gain reflecting cummulative increase in output as units are sequentially driven out of deadbands. However, this model produced somewhat different results.

AGC SIMULATION WITH DEADBANDS

Step and stochastic load changes were simulated. The system representation included 10 Pacific Northwest Federal hydro powerplants and 2 or 3 equivalent plants for each of 13 interconnected AGC areas. Steam generation equivalents consisted of single reheat units with the deadband models described above. Several hundred discrete deadbands were thus represented in 40 generation equivalents.

Figures 5 and 6 show the effect of the deadbands for a 100 MW step load increase. The deadbands cause a larger initial frequency deviation and a more oscillatory response. Simulation experiments showed that the more oscillatory response was principally due to the faster responding steam generation rather than the hydro generation.

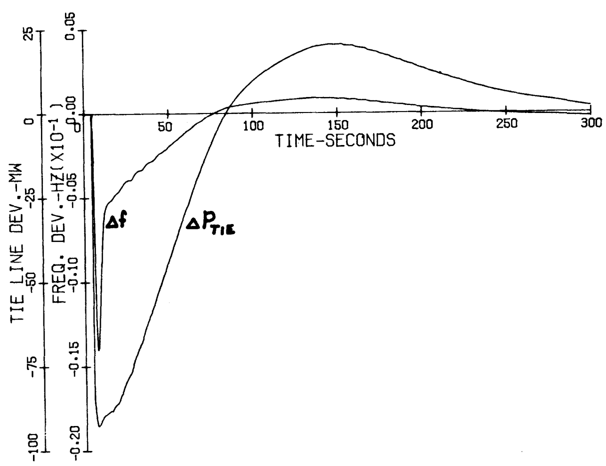

Fig. 5. Simulation response of system frequency deviation and tie-line power deviation for 100 MW step load increase. Without deadbands modeled.

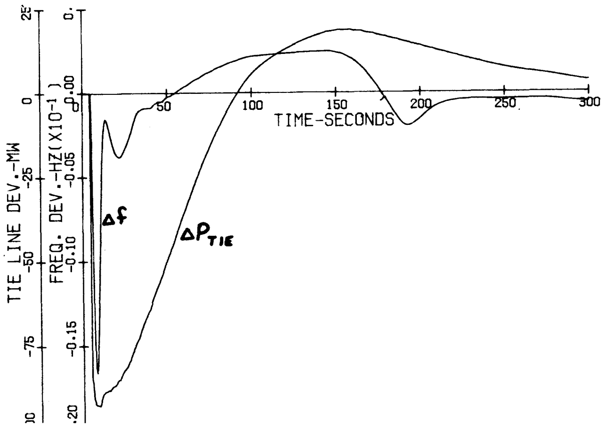

Fig. 6. Simulation response of system frequency deviation and tie-line power deviation for 100 MW step load increase. With deadbands (mean .0001, 3 sigma .00005).

Figures 5 and 6 show that system frequency deviation had higher frequency components than tie-line power deviation. These frequencies were reflected in ACE. As expected, system frequency initially dropped at a rate determined by system inertia. Governors arrested the drop at about 3 seconds and then, within about the next 10 seconds, restored the system frequency according to the droop settings. System frequency is then reset to schedule by AGC. On the other hand, tie-line power is initially changed according to synchronizing power coefficients (not represented in simulation) and then according to the inertia values in each area. If governor responses are uniform and in proportion to area inertias, tie-line power will not change from its value just following the disturbance until AGC become effective 10-20 seconds later. For stochastic analysis, the above analysis may explain the high coherence of ACE and system frequency throughout the spectrum studied.

Figure 7 shows the effect of the normal distribution of deadband widths for a 50 MW step change in load. Curve A shows response of system frequency response for 0.0001 p.u. mean deadband widths with 3 sigma values of 0.0001 p.u. Curve B shows response with all deadbands widths equal to 0.0001 p.u. The effect of the normal distribution is to reduce the magnitude of the oscillatory response.

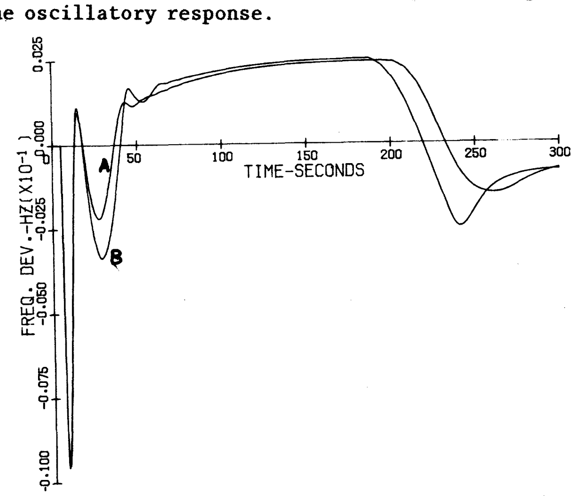

Fig. 7. Simulation response of system frequency deviation for 50 MW step load increase. Curve A with normal distribution of deadbands widths. Curve B with all deadband widths equal.

Stochastic simulations were run with power spectral density estimates computed for system frequency deviation using the methods described above for the real system data. Simulation length was 8,192 seconds with spectral lines averaged from 16 segments.

Results are shown on Figure 8 and should be compared with the corresponding real system shown on Figure 2. The primary effect of the deadbands is increased spectral power in the 2-10 cycle per minute range. This would indicate that deadbands affect the performance of the primary speed governors control more than AGC. Comparison with the real system data indicates a closer comparison without the modeling of deadband effects. It would thus appear that governor deadbands are less important in the AGC process than previously suspected. Simulation program improvements and enlargements may change the comparisons somewhat.

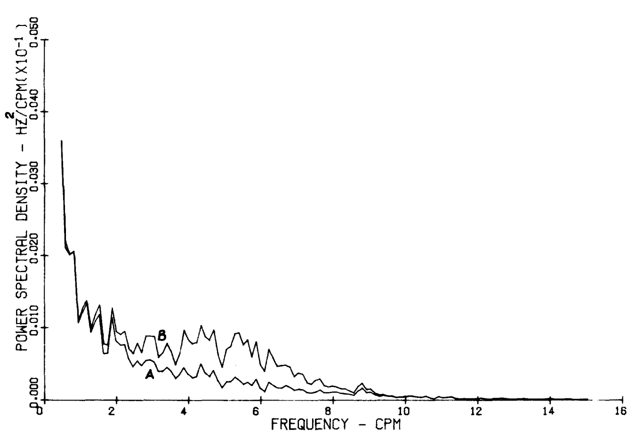

Fig. 8. Power spectral density functions of system frequency deviation from simulation. Curve A without deadbands, Curve B with deadbands (mean 0.0001 pu, 3 sigma 0.00005 pu).

Using a 0.0001 p.u. mean deadband width on all generation, several stochastic simulations were run with frequency bias coefficient, B, for all control areas set equal to the system characteristic, β, and also with B set equal to 2β (corresponding to light system loading). The deadband effect was ignored in computing B. Depending on plant response characteristics and ACE probability filter characteristics, control pulses to governor speed reference motors were increased by factors of 1.5 to 5 with B = 2β. AGC performance statistics were changed less than 15%. These results suggest adapting bias coefficient values to system loading may be effective in reducing unnecessary control action. Varying bias coefficients according to disturbance size, however, does not appear useful.

Bias settings adaptive with system loading would be easy to implement in modern control centers employing digital computers. Adaptive bias settings would be consistent with the underlying basis of the area control error concept. If desireable, the bias settings could be increased to the heavy loading value for large frequency deviations.

CONCLUSIONS

Results from statistical analysis of both heavy and light load real system data records have been presented. Composite deadband effects have been represented in a large AGC simulation program and analyzed. Analysis of system data during normal operating conditions indicated a high correlation between system frequency and Area Control Error throughout the 0.5 to 15 CPM spectrum for both heavy and light load conditions. Well defined limit cycle frequencies were not detected. Throughout the spectrum, the power spectral density of system frequency was much higher for the light load data. This is probably due to reduced inertia of generating plants along with different random load change patterns and magnitude.

Comparison of stochastic simulation results with the system data indicates that deadband effects in the AGC process may be small. Simulation results also indicated varying AGC frequency bias coefficients according to system loading may reduce unnecessary control action.

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Discussion

D. N. Ewart (General Electric Company, Schenectady, NY): This paper is a welcome contribution to the literature on the control of interconnected power systems because it provides significant field data, analysis of the data plus associated simulation results. I have several observations to make and some questions for the authors.

First, I believe the high degree of correlation between ACE and system frequency, which the authors found in their analysis of measured data, is very significant, particularly in the lower end of the frequency spectrum. This confirms my own conjecture based upon visual observation of chart recorders over a period of time. This finding, in itself, must lead one to conclude that regenerative processes are occuring; i.e., that unit response to ACE-derived commands contribute to the frequency excursions. That the authors found no dominant frequency of oscillation in the spectral band width studied is interesting but not conclusive. Is it possible, for example, that Curve B on Figure 2 shows evidence of a resonant peak at about one cycle in 100 seconds? Since a large power system interconnection is likely to be nonstationary over the spectral range where AGC-caused resonances would occur, expectations which are based on classical control theory must be modified. Instead, we must look for more subtle clues. It would have been helpful if a plot of a frequency trace used for analysis had been included in the paper. Perhaps the authors could include one in their closure.

The authors correctly surmise that modern speed control systems probably have much less deadband than permitted by current standards, but to assume that all units on the interconnection have low deadband may not be realistic. Typically, in fact, many of the units presently under AGC are older and may have deadbands which approach or even exceed standards.

No mention is made of the AGC gain used by BPA in their control center or in the simulations. Without knowing this parameter, it is difficult to comment on the simulation results. Could the authors please indicate for the BPA system, how many MW per second of composite response is requested by the AGC system for a MW of ACE, (in the linear range)?

What steps were taken to avoid signal alaising? It is stated that an analog frequency signal (digitally derived) was filtered with a first-order lag of 0.3 second and then sampled at two-second intervals. It would appear that the possibility of alaising exists.

It is stated that a non-linear governor characteristic used to stimulate deadband produced results which were different from those obtained with a composite deadband. Could the authors please characterize the difference?

AGC systems, when stripped of their appurtenances, are really very simple. The process being controlled, namely the power system, is not simple at all. It is of high order, non-linear and non-stationary. This paper, by presenting and analyzing field data, has made a positive contribution to understanding the process and therefore to the state of the art.

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D. K. Pantalone (Clarkson College, Potsdam, NY): The authors' analysis has provided some very useful insight into AGC performance. They are to be particularly commended for bringing to bear on the problem being investigated several tools of stochastic analysis, such as power spectral density functions, cross correlation functions, coherence functions, and the run test. However, some of the results shown in the paper seem to contradict the conclusions of the paper.

The particular limit cycling phenomenon that was noted by Ewart (reference [8] of the paper) occurred with a time period ranging from 30 to 90 secs. This corresponds to a frequency range of 0.66 to 2.00 cpm which is at the very low end of the frequency spectrum studied in the paper (.5-15.0 cpm). The authors correctly caution the reader about the problems of nonstationarity that arise when long data records are used, the length of which must be longer when lower frequency spectral content is being measured and when time series data is being used. Nonetheless, when a particular finite frequency band is of interest, an adequate analysis should extend reasonably beyond this band on both sides. Despite the above measurement and analysis problems, Figures 2 and 8 of the paper clearly show a sharp rise in the power spectral density of system frequency deviation between .5 and 3.0 cpm (particularly for light load conditions). Contrary to the stated conclusions of the paper, this would seem to present some evidence of distinguishable oscillation or limit cycling. Furthermore, this evidence coincides with the frequency range of the limit cycling observed by Ewart.

The information gathered from the spectrum of frequencies studied in the paper is of definite value. The results do seem to show, among other things, that the most prominent effect of governor deadband in the system as modeled is above 2.0 cpm. Yet, because of the frequency range chosen, the questions raised by Ewart concerning the existence of 30 to 90 sec limit cycles have not been fully answered and certainly not refuted. This research area is presently being investigated by this discusser as well.

Limit cycling is a well known phenomenon of nonlinear systems. Although Ewart's hypothesis on the influence of governor deadband in particular on AGC limit cycling seems not to be supported in this paper, another reference ([1] below) indicates one actual instance where governor nonlinearities influenced a limit cycling of a particular steam power plant. The frequency of this plant's limit cycle, though, was in a range of 4.0 to 7.5 cpm. Concerning the 0.66 to 2.00 cpm AGC limit cycle, however, it should be noted that aside from governor deadband, other nonlinearities exist in prime mover systems, and that the slower prime mover dynamics influence lower frequency limit cycles. With regard to adequate analysis of a lower spectrum of frequencies, further effort must be made to overcome the problem of nonstationarity. With due regard to resolution and confidence level, analysis of multiple records of system data taken at different times during which system loading conditions, generation mix, and time of day are sufficiently similar, may be helpful.

The authors have mentioned possible dither modulation effects that high frequency oscillations of generator rotors may have in reducing effective governor deadband widths. In fact, such phenomenon has been known by governor manufacturers for several decades and has been used by them as an actual part of hydraulic governor design to minimize effective deadband. According to one manufacturer, it is possible to reduce deadband with such techniques to less than .001%, a value that would never be possible in certain designs without the dither. Nonetheless, as with other equipment in power plants, field installation does not usually result in the finest tuning possible, especially if a standard requires deadband to be limited to only .06%.

The paper has made use of two methods for representing composite deadbands. The second method was only briefly mentioned. Could the authors give any references containing more detail on the second method, and also indicate how the results that were produced with this method differed from the results shown? Furthermore, is not the aggregate deadband modeling method contained in reference [13] of the paper different from either of the two methods used in the paper?

A major subject of the paper is the correlation between ACE and system frequency deviation. The authors have perceptively noted that after a large disturbance and between the time when governors first begin to act (a few seconds after the disturbance) and the time when AGC becomes effective (10 to 20 seconds later), tie-line power will not change much if governor responses are essentially uniform and in proportion to area inertias ([2] below). This would correctly imply a high correlation between ACE and system frequency deviation during these initial governor oscillations. However, care should be taken in trying to generalize this observation as an explanation of the coherence functions shown earlier in the paper.

The particular theoretical correlation above was hypothesized as occurring during a relatively short time period in the middle of a long transient following a large abnormal disturbance. If one was to analyze this short intermediate time period specifically, one might expect to get a coherence function approaching unity. However, since the time period is limited to approximately 20 secs in length, the frequency spectrum over which such a coherence function could be determined is ideally limited to roughly 3.0 cpm and above (ignoring sampling rate, resolution, and confidence level aspects). Yet, the fundamental frequency of the governor oscillation that occurs during this time period itself seems to be centered around 3.0 cpm. On the other hand, the coherency functions plotted in the paper were calculated from two continuous data sets extending over 2 and 3 hours, the latter of which apparently had no sudden or major disturbances. The frequency spectrum over which these coherency functions are plotted is the .5 to 15 cpm range covered throughout the paper. This range of spectrum and this length of data record imply that many more phenomena are represented than can be easily explained by the limited but instructive theoretical hypothesis above.

In conclusion, I would once again like to compliment and thank the authors for their significant and thought provoking contribution to this subject. They have made long strides in the type of analysis techniques used, in analyzing both real system data as well as simulation data, and in showing the effects of distributed nonlinearities in a large system simulation. The results of their work add another piece to a complex and yet unfinished puzzle.

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C. W. Taylor, K. Y. Lee, and D. P. Dave: The discussors raise a number of questions and contribute valuable comments.

Mr. Ewart and Dr. Pantalone both correctly argue that the real system data indicates the possibility of limit cycles. The conclusion of the paper that effects of deadbands appear to be small was based on comparison of the real system data with simulation—compare Figure 2 with Figure 8. We should have noted and emphasized that the system data taken alone can support a limit cycle hypothesis.

As requested by Mr. Ewart, Figure 1 shows a time domain plots for the August 6, 1977 data record.

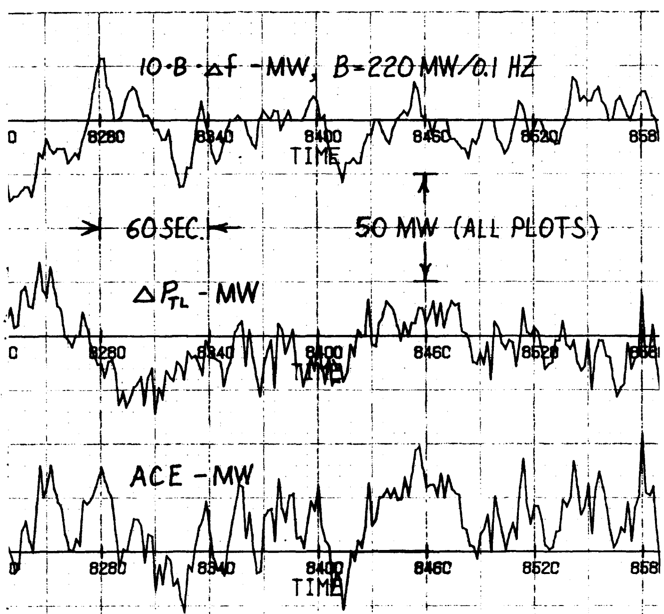

Figure 1. Time domain plots of frequency deviation (multiplied by bias), interchange power deviation, and area control error. Data recorded at BPA control center on August 6, 1977; 0101 - 0401 hours.

Mr. Ewart suggests that older units typically used for AGC (in thermal powerplant systems) may have larger deadbands. This may very well be true and we did some additonal simulation using this suggestion. Limit cycles with periods in the 30-90 second range were obtained. However,other parameter changes were also required. These included both increasing the plant controller gains and eliminating intentional relay type deadzones in plant controllers. The ± 5 MW deadzones assumed for plant controllers greatly reduced the tendency to limit cycle. The limit cycles resulted for light load simulations only. Reduction of frequency bias for light load reduced the tendency to limit cycle.

Regarding AGC gain used by BPA, generation response for an ACE is determined by controllers in the various hydroplants and by the governor-turbine characteristics. In actual practice a rather wide range of responses are obtained for step change commands. These vary from fast and oscillatory, to "well-tuned", to sluggish. For the simulations, gains were adjusted to obtain typical fairly fast responses with small overshoot. For a 30 MW command, a 25 MW generation change (lower boundary of controller deadzone) was reached in 50–80 seconds. Rise time from 3 to 25 MW was 40–55 seconds. Some of the thermal plants modeled responded faster than this.

We agree with Mr. Ewart that a possibility of aliasing exists. The method of recording did not conveniently allow additional filtering over what is presently used in the BPA AGC system. However, tests have indicated that aliasing does not appear to cause problems. As an example, a dominant low frequency mode of about ⅓ Hz (20 CPM) exists in the western interconnection associated with the Pacific AC Intertie. This is observed on system frequency recordings at the BPA control center for large disturbances. The 2 second sample rate used in the analysis corresponds to a Nyquist or folding frequency of 15 CPM. If aliasing of this mode was present during normal operating conditions, the 20 CPM oscillations would be folded back to 10 CPM and result in peaking of power spectral density at 10 CPM. There is no peaking present on Figure 2 of the paper or on similar unpublished data. We are aware of one large utility that successfully employs a four second sample rate for AGC without any anti-aliasing filtering.

Both Mr. Ewart and Dr. Pantalone ask about the second deadband model which was briefly mentioned in the paper. Compared with the step load change response shown on Figure 6 of the paper, the non-linear gain deadband model caused 20–24 second period oscillations in system frequency rather than the highly non-linear response of Figure 6. This model was criticized for not including memory characteristics. The model in Reference 13 is different from either of the models in the paper.

Dr. Pantalone comments about extending the low end of the frequency domain analysis. In future work it might be desirable to divide the data into a number of frequency domain segments and examine the stationarity of each part of the spectrum. This would help determine the feasibility of analyzing lower frequencies.

Several additional comments should be made regarding the stochastic analysis. The paper is partly in error in that a 256 point transform was used with 512 second record length, $\Delta t = 2$ second, and $\Delta f = .118$ CPM. The minimum random error or variability is equal to the inverse square root of the number of independent (non-overlapped) records. For a 2 hour data record, random error exceeds $100/(7168/512)^{1/2}$ or 27 percent. This emphasizes the difficulty of meaningful stochastic analysis.

Dr. Pantalone discusses the correlation of ACE and system frequency along with relationships between step disturbances and stochastic analysis. The analysis in the paper pertaining to Figures 5 and 6 (simulation of step load changes) actually do not require large disturbances. The 100 MW step load change used would be about a 0.13% perturbation to the western interconnection with smaller perturbations producing similar results. We agree that care is required in generalizing deterministic analysis to the stochastic case. This generalization is strickly valid only for linear, stationary systems.

We now routinely analyze the frequency domain of deterministic (step load change) AGC transients via the same power spectral density computations described for stochastic analysis. The time domain plots would be similar to Figures 5–7. The same 256 point transform with double (squared) Hanning data window is used with the transient initiated near the middle of the 512 second simulation. Coherence functions could be computed by this technique throughout the 0-15 CPM range.

Dr. Pantalone's remarks on dither modulation and the limit cycling reported in his Reference 1 are of particular interest to us.

We thank the discussors for their contributions and for the opportunity to clarify the paper.

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