Master

Wind Power Generation Dynamic Impacts on Electric Utility Systems

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Technical Planning Study TPS 79-775

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ABSTRACT

A primary application of wind power generation on utility systems is expected to be large clusters of megawatt-scale wind turbine (WT) units, connected to the utility transmission network and operated as part of the overall utility generation mix. Wind fluctuations will result in minute-to-minute WT output variations. Large penetrations of wind turbines may cause dynamic impacts such as severe system swings, excessive frequency excursions, or system instability. These potential dynamic impacts, considering the integrated wind power plants, utility conventional generation, and transmission system, may limit the potential WT penetration and/or cause significant system operating restrictions. An initial assessment of potential wind power generation dynamic impacts on utility systems from a global utility perspective was made. Dynamic study of minute-to-minute ramping, frequency excursion, and short-term transient stability was performed using the Hawaiian Electric Company system as an illustrative example.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This technical planning study (TPS 79-775) was an initial EPRI assessment of the potential dynamic impacts on electric utility systems that may be attributable to wind power generation using clusters of large wind turbines. Three classes of dynamic problems were examined: (1) short-term transient stability, (2) system frequency excursions, and (3) minute-to-minute unit ramping limitations of the conventional system generation. Case studies were performed using the Hawaiian Electric Company (HECO) system as an example. The HECO system is isolated; i.e., not interconnected with other utility systems. The dynamic problems examined in this study tend to be more pronounced on an isolated system than on an interconnected system. However, an effort was made to generalize the study conclusions wherever possible.

In performing the transient stability analysis, a simplified model of a wind turbine cluster was used which was adequate for an initial assessment of utility system impacts. However, this model is not suitable for examining certain classes of dynamic problems, such as wind turbine interactions within a cluster, which were not treated in this study. Furthermore, the model has other limitations and a more detailed study of dynamic problems would require a more sophisticated model. In general, the relative importance of the three dynamic problem areas discussed above was determined using simplified computational techniques. The results and conclusions can be used as a guide in planning future detailed assessments of the system dynamic impacts of wind power generation.

PROJECT OBJECTIVES

The major objectives of this study were: (1) to identify potential dynamic problem areas that may exist for utility systems with large penetrations of wind turbines in their generation mix, (2) to develop study methods for assessing potential dynamic impacts and apply these methods to a case study example, and (3) to use the case study results in formulating conclusions about the relative importance of various dynamic problems as a basis for defining future, more detailed dynamic assessments of this type.

PROJECT RESULTS

Dynamic problems may limit the ultimate penetration of wind turbines into electric utility systems. This penetration limitation is more likely to exist for small, isolated utility systems than for large interconnected systems in which other factors may limit penetration. In any case, operating restrictions may have to be placed on large wind turbine clusters (which may lower their annual energy production) in order to achieve the most economical operation of the overall utility system of which the cluster is a part.

It appears that short-term transient stability will not be endangered by the addition of wind turbines to either isolated or interconnected utility systems. Restrictions on allowable system frequency excursions during a sudden wind change may limit wind turbine penetration in isolated utility systems, depending on the operating criteria in specific cases. Frequency excursion limitations are not a problem for interconnected utility systems, because operating practice is based upon other criteria such as area control error. Restrictions on allowable ramping rates of conventional generation during a sudden wind change may limit wind turbine penetration in both isolated and interconnected utility systems. This dynamic problem is most severe when a large wind change occurs simultaneously with (or within a few seconds of) a large change in system demand under light loading conditions, so that the combined effect requires a steep ramping up or down in the conventional generation mix. Wind turbine penetration limitations together with alterations of traditional operating practice may be required to alleviate this problem.

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ACKNOWLEDGMENTS

The project team for this study included Zaininger Engineering Company (ZECO), supported by their subcontractor, JBF Scientific Corporation. JBF project contributors were T.F. McCabe and J. Singh.

A key aspect was the involvement and interest of Hawaiian Electric Company (HECO) in this project. Close interaction between HECO engineers (especially R.M. Belt, Principal Planning Engineer) and ZECO insured project success and realism of study results.

Many thanks to A. Daniels of the University of Hawaii for supplying the wind fluctuation data used in this study.

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SUMMARY

This report summarizes the work performed by Zaininger Engineering Company (ZECO) for the Electric Power Research Institute (EPRI) under Contract TPS 79-775.

The purpose of the study was to perform an initial assessment of potential wind power generation dynamic impacts on electric utility systems. A range of "worst case" wind fluctuations was examined using the Hawaiian Electric Company (HECO) system for case studies. Minute-to-minute system generation ramping, frequency variations, and short-term stability were assessed. A global approach to identifying potential dynamics problems was taken with several primary objectives: 1) to develop appropriate study methods for assessing dynamic impacts of large penetrations of wind power generation; 2) to apply these methods to an illustrative example utility system; and 3) to analyze results and draw general conclusions regarding potential wind turbine (WT) penetration limits attributable to dynamic problems.

The project approach consisted of several tasks. The appropriate HECO generation, transmission, and load representation were determined based upon 1985 HECO projections. A two-mass wind turbine dynamic model was developed from the best available information. HECO frequency excursion and ramping criteria and operating experience were examined and compared with operating criteria of the North American Power Systems Interconnection Committee (NAPSIC). Appropriate "worst case" wind fluctuations representative of the total WT cluster were then examined using the limited available minute-to-minute wind data.

Frequency excursion and minute-to-minute ramping calculations were performed for a range of wind turbine cluster sizes, initial operating conditions, and different frequency excursion and ramping criteria. These cases were associated with day-to-day normal operation "worst case" assumptions. The calculations were performed on a parametric basis because of the lack of existing minute-to-minute wind fluctuation data and coincident wind power plant performance model. For example, Figure S-1 presents the maximum allowable combined wind power plant

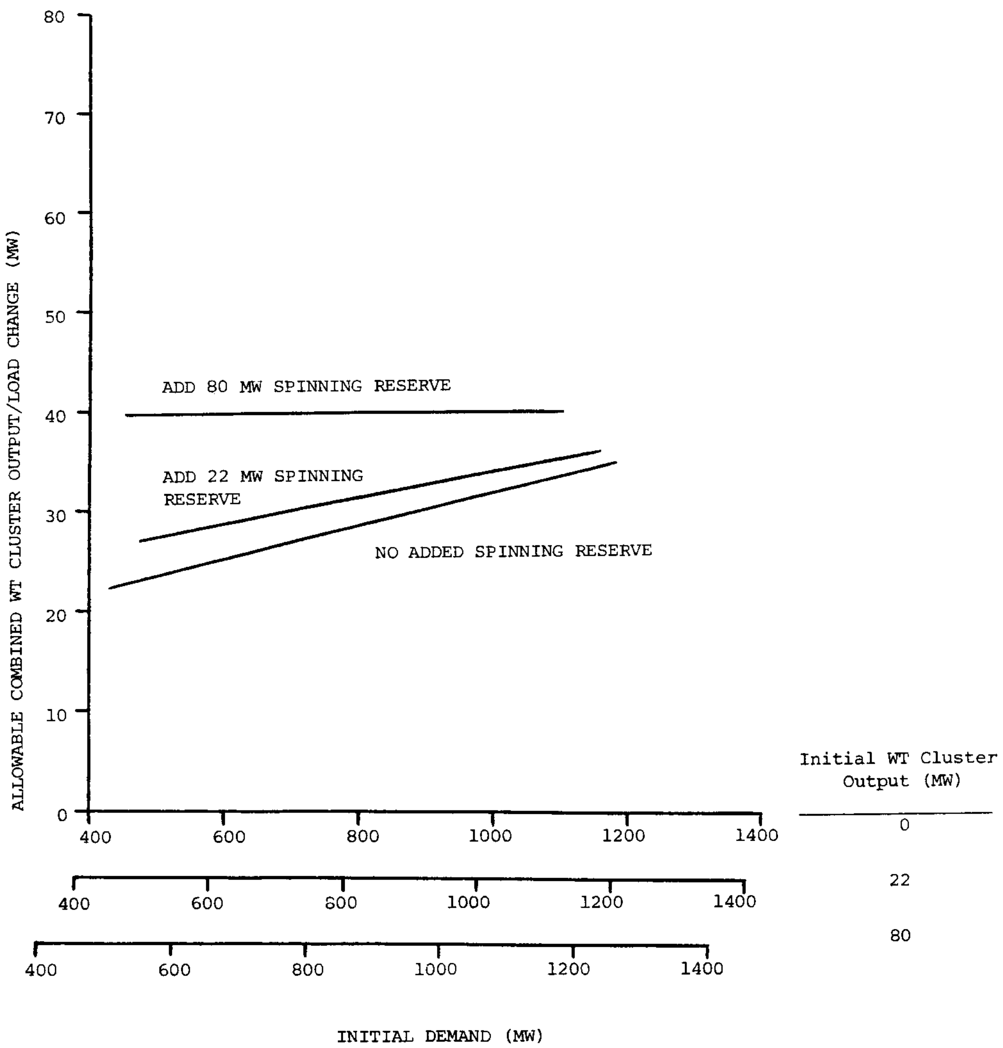

Figure S-1. Allowable Combined WT Cluster Output/Load Change Corresponding To A 0.1 Hz Frequency Excursion. A combined WT cluster output/load change means an increase (or decrease) in WT cluster output and simultaneous decrease (or increase) in system demand.

output/load change to limit system frequency excursions to 0.1 Hz. This figure presents data for a range of initial system load levels, spinning reserve criteria, and initial WT cluster output levels.

Figure S-2 presents the maximum allowable combined WT cluster/load change in a three minute period as a function of initial system demand. These data are plotted using allowable HECO three minute ramping criteria and operating reserve criteria.

Short-term transient stability calculations were performed assuming several "worst case" HECO system disturbances. In all cases studied, the HECO system was stable with and without up to 80 MW of wind turbines installed. For example, Figure S-3 presents one of the transient stability cases. In this case, under peak load conditions, the total 80 MW wind plant was tripped, and the HECO system remained stable.

Some general conclusions and observations resulting from this study are as follows:

- Utility system dynamic impacts may limit the potential penetration of wind turbines.
- Operating restrictions on large wind power plants due to dynamic impacts will tend to reduce their annual energy output. Hence, annual energy projections for large wind power plants should account for these restrictions.
- There is little representative minute-to-minute wind data presently available for assessing dynamic impacts of large clusters of wind turbines.
- An important potential dynamic constraint to WT penetration is minute-to-minute ramping requirements imposed on the rest of the system generation on a daily basis. This statement applies to both isolated and some interconnected utility systems.
- System frequency excursion limitations are an important dynamic consideration for isolated utility systems.
- Dynamic impacts of wind turbine clusters will be site specific.
- Consideration of wind plant output fluctuations under utility light loading conditions, as well as peak loads, is important.
- The conclusions of this study are considered as preliminary, due to the present lack of suitable site specific wind data and field experience with large clusters of wind turbines.

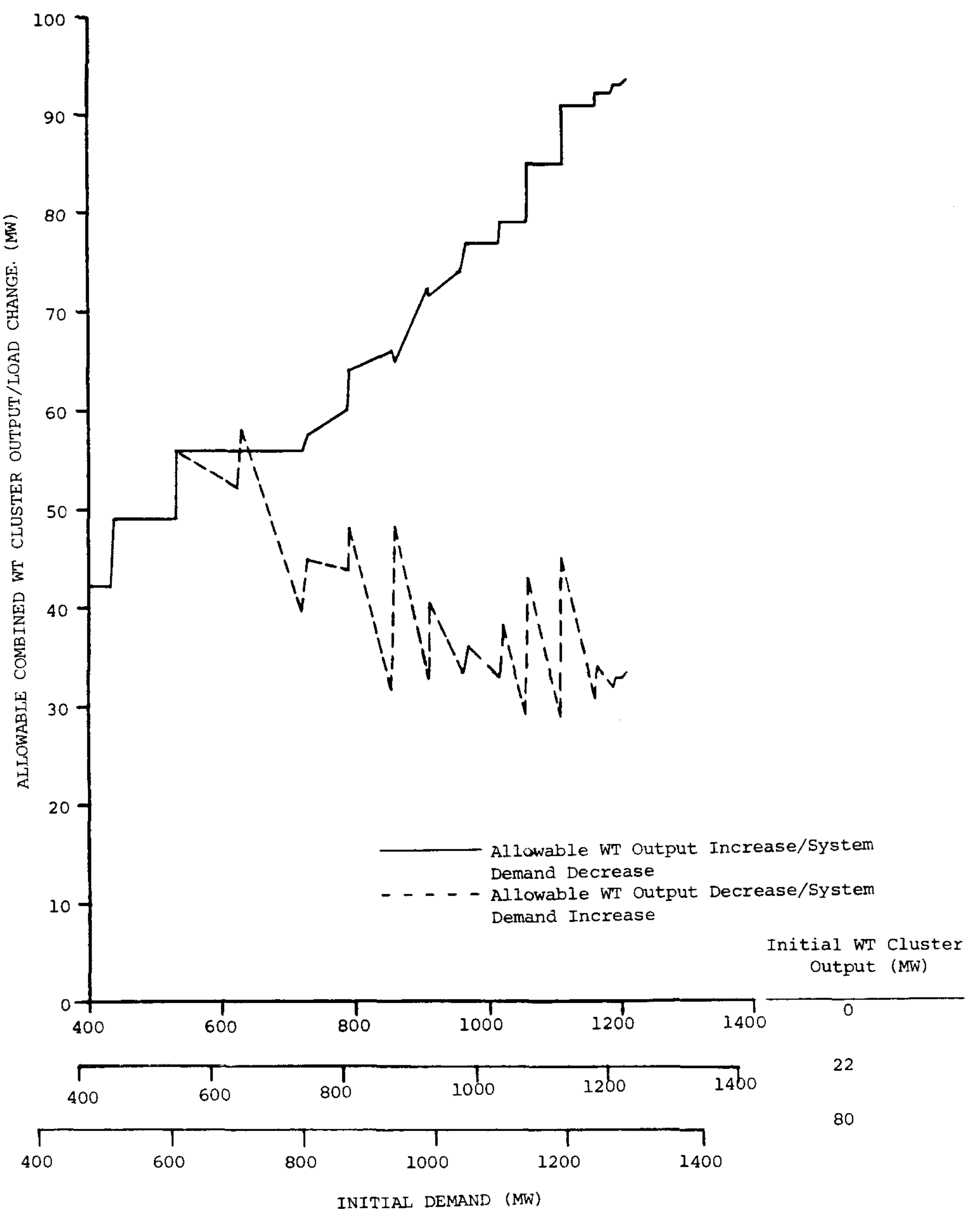

Figure S-2. Allowable Combined WT Cluster Output/Load Change In Three Minutes Using Allowable Three Minute HECO Generation Ramping Criteria

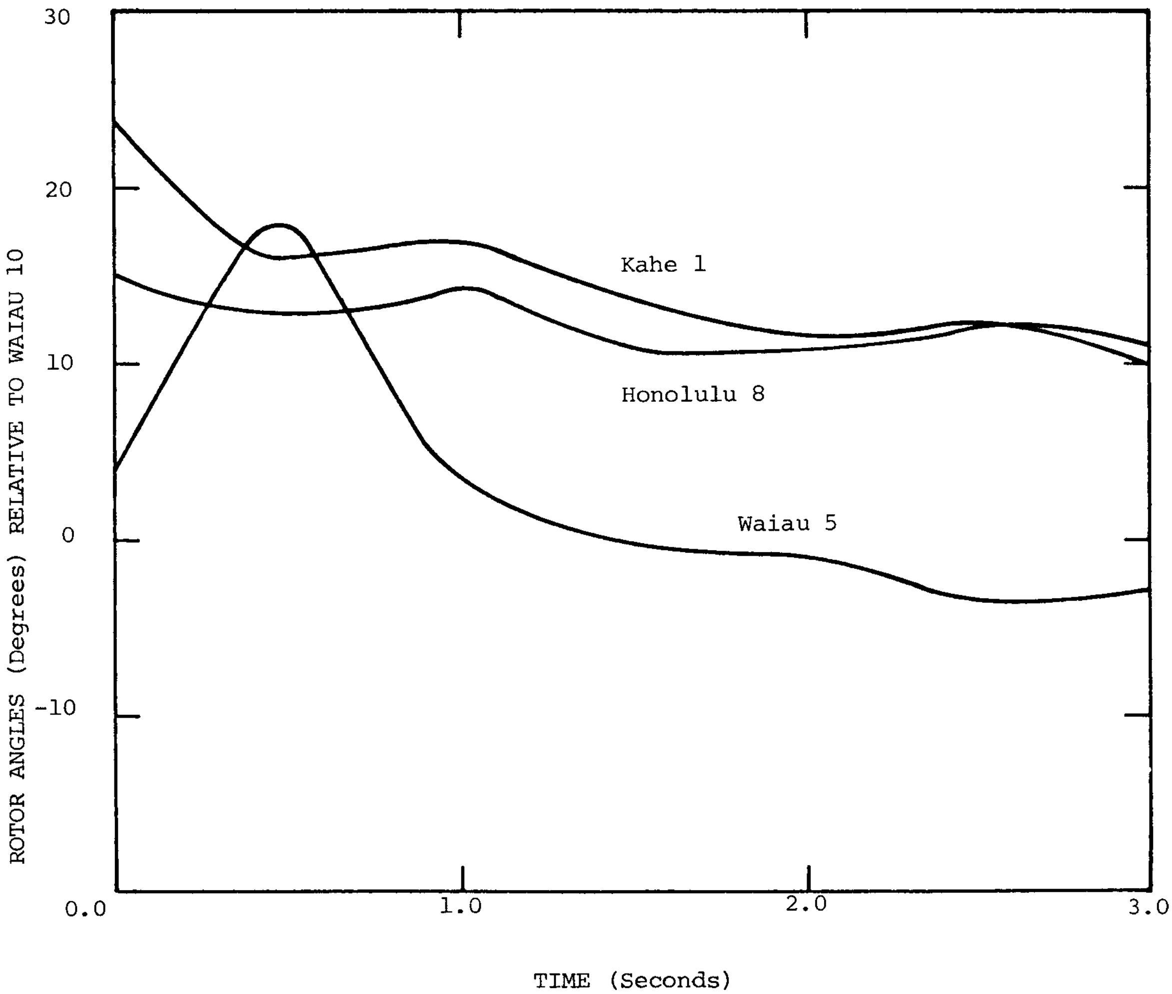

Figure S-3. Generation Swing Curves For Tripping 80 MW WT Cluster At Peak Load

Section 1

INTRODUCTION

A primary application of wind power generation on utility systems is expected to be large clusters of megawatt-scale wind turbine (WT) units. These wind power plants will be connected to the high voltage transmission network similar to conventional generation, and will operate as part of the overall generation mix.

The WT's are an intermittent source of energy. Minute-to-minute wind fluctuations will result in variation in WT output. On a minute-to-minute basis these variations may cause severe system swings, frequency variation, or system instability when WT penetration is sufficiently large. These minute-to-minute power system dynamics may limit the potential WT penetration on utility systems.

Power system dynamic analysis requires appropriate representation of the generation, transmission system, and load. Depending on the purpose of the dynamic analysis, power system representation varies in detail. The thrust of previous wind power generation stability studies (1, 2) has been to determine WT unit dynamic performance. In these previous studies, the utility generation and transmission have been represented in a very simplified manner such as an infinite bus. No prior dynamic analysis has been made of a utility generation and transmission system with a large penetration of WT's installed.

The purpose of TPS 79-775 was to make an initial integrated WT/utility system dynamic analysis. In this study, the total utility system dynamic performance with wind power generation installed was examined from a global utility perspective. The study was an initial step in determining potential WT penetration limits attributable to dynamic problems.

An initial case study of WT dynamic problems was made using the Hawaiian Electric Company (HECO) system. However, this study was not intended to cover all dynamic considerations, as the HECO system is isolated and relatively small. For example, this study did not include potential dynamic impacts with long transmission lines, EHV transmission, or response of very large generation units.

The primary objective was to put WT dynamic problems in perspective from a global point of view. The relative importance and order of magnitude of potential WT/utility dynamic problems for a range of WT penetration levels were examined. Potential frequency excursions and minute-to-minute ramping requirements were determined on an everyday system basis, using a "worst case" approach. System stability calculations were performed for severe system disturbances.

Section 2

ASSUMPTIONS AND BACKGROUND INFORMATION

This section presents assumptions and background information used in this study. These data are supplemented by the data contained in the appendices.

HECO SYSTEM DESCRIPTION

Appropriate generation, transmission, and load data for this initial, global, dynamic assessment were obtained from Hawaiian Electric Company (HECO) and supplemented by typical data (3) for use in these calculations. The following HECO system description is based on HECO projections for their Oahu system in 1985, as of early 1980.

The projected HECO 1985 generation system for Oahu consists of 20 units located in three generating plants, Kahe, Waiau, and Honolulu, as shown in Appendix A. The projected total installed capacity is approximately 1349 MW, with 638 MW installed at Kahe, 531 MW installed at Waiau, and 180 MW installed at Honolulu. All the units except W 9 and W 10 are oil fired steam units. W 9 and W 10, both 52 MW, are combustion turbines. Generation governor response characteristics (4) assumed for frequency excursion calculations are presented in Appendix B. HECO system priority order and generation ramping rates used for minute-to-minute ramping calculations are presented in Section 4. Machine data assumptions are presented in Appendix C.

In this study, the base case WT cluster is assumed to be 80 MW, installed at Kahuku. The WT dynamic model assumptions are presented in Appendix D.

A one-line diagram describing the projected HECO 138 kV transmission system on Oahu used for this study is shown in Figure 2-1. The projected HECO transmission system on Oahu for 1985 consists of approximately 200 miles (322 km) of 138 kV lines, as described in Appendix A. The Oahu transmission system is isolated in that the islands are not interconnected. The longest 138 kV line on Oahu is approximately 21 miles (34 km) long. The HECO generation/transmission/load system

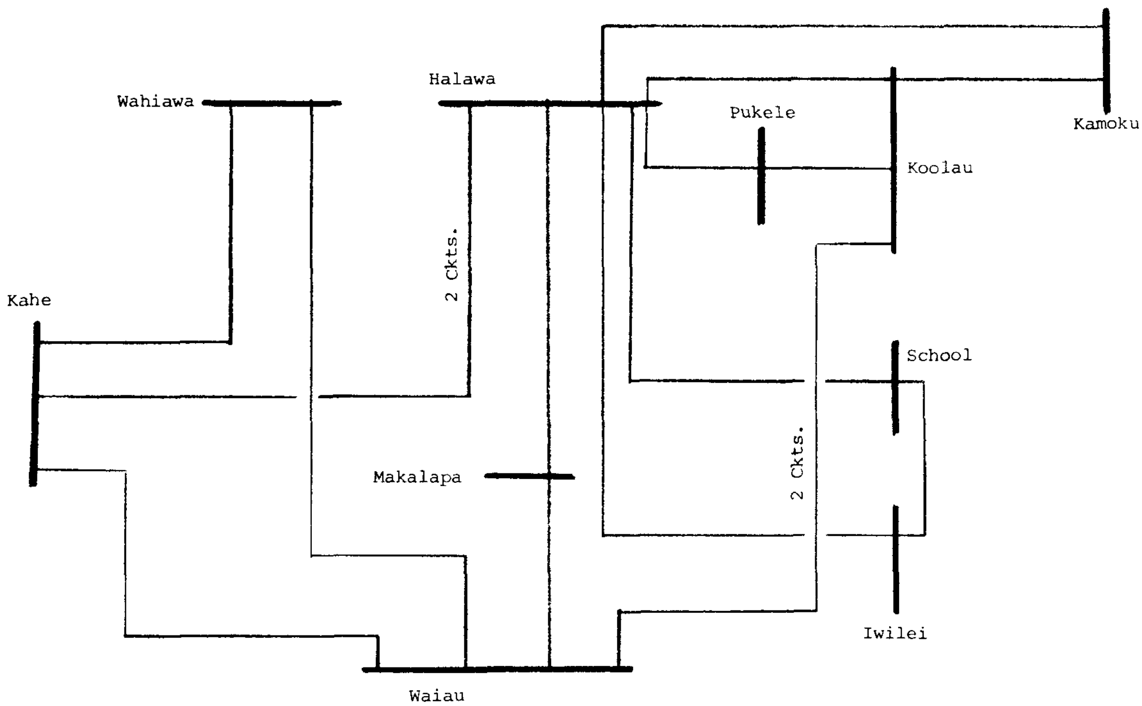

Figure 2-1. 138 kV HECO Transmission System One-Line Diagram

can be classified as very dense, or concentrated, as the generation is situated very near the load. A measure of this density is that there are less than 0.2 miles (0.32 km) of bulk transmission facilities per MW of peak load served.

The HECO transmission system impedance data used for the stability calculations are also presented in Appendix A. These data consist of impedance data for the nineteen 138 kV lines shown in Figure 2-1. Impedance diagrams for the Kahe and Waiau power plants are included, along with the impedance representation used for the Honolulu area. The Honolulu area is represented by two 138 kV buses, School and Iwilei, plus some equivalent 46 kV and 11 kV representation.

The base case 80 MW wind turbine cluster was assumed to be installed at Kahuku on the north side of Oahu and connected to the HECO transmission system at Wahiawa via 16 miles (26 km) of 138 kV line. The impedance representation for this 80 MW wind plant, as well as 22 MW of WT's connected to Wahiawa via the existing 46 kV system, are also contained in Appendix A.

The HECO system native peak load projection for 1985 used in this study was 1136 MW, including losses. The projected minimum load was 477 MW. A breakdown of bus loads and losses assumed is presented in Appendix A.

MINUTE-TO-MINUTE WIND POWER PLANT OUTPUT FLUCTUATIONS

The potential dynamic impacts of large penetrations of wind turbines are a function of the following:

- Minute-to-Minute Wind Fluctuations
- Individual WT Output Response
- Coincident WT Plant Output Fluctuations

At the present time there is little operating data available regarding these parameters. Hence, the approach in this initial assessment was to establish a range of potential dynamic impacts for reasonable "worst case" assumptions. First, for short-term stability calculations, typical "worst case" assumptions were that either the total WT plant or other large generation trips off-line. If the system is stable for these severe, unlikely cases, it is also likely to be stable for less severe transients that occur more frequently. These "worst case" short-term stability calculations are independent of the magnitude of minute-to-minute wind fluctuations, and corresponding coincident WT plant output fluctuations.

The second class of problems pertains to potential dynamic impacts on a less severe, day-to-day basis. These daily dynamic impacts consist of potential system frequency excursions and minute-to-minute system generation ramping requirements. Calculations were performed for potential "worst case" minute-to-minute wind plant output fluctuations expected on a daily basis.

Although little minute-to-minute data are presently available, six hours of wind fluctuation readings taken in one second intervals at Kahuku were obtained from the University of Hawaii. Although this is a small sample, it is expected that "worst case" wind fluctuations will be at least as great as those in these data. The following paragraphs develop expected minute-to-minute wind power plant output using these wind data, individual WT output response, and total coincident WT cluster output assumptions.

In October 1978, the University of Hawaii gathered approximately six hours of one second wind fluctuation readings in the Kahuku area. These data consist of seven runs of approximately 3000 seconds, taken at three different sites on different days, with the anemometer at a height of 30 feet (9.1 m). The average wind speed during the seven runs ranged from 13.3 mph (6.0 m/s) to 15.5 mph (7.0 m/s).

As part of this study, the one second readings were plotted, along with 10 second, 30 second, and 60 second integrated wind fluctuations. Based on these plots, the 600 second period contained in Appendix E can be considered a typical "worst case" for the six hours of wind fluctuation data. Considering the one second readings, 10-18 mph (4.5-8.0 m/s) wind fluctuations can be expected in a ten second period.

In order to evaluate the potential minute-to-minute dynamic impacts of wind power plants on utility systems, it is essential to model individual WT output response to wind gusts and to develop coincident total WT cluster output fluctuations. As stated previously, there is little precedent for modeling the response of a large wind turbine to minute-to-minute wind fluctuations. There are two factors which must be considered when modeling WT response. The first factor is to correlate the wind measurement at a given height with the wind impinging on the large 250-300 foot (76-91 m) rotor. The second factor is to incorporate the WT inertia in determining WT response. In addition, when modeling the potential impacts of multiple WT unit swings on utility systems, a coincidence factor must be applied when summing up the minute-to-minute output fluctuations of the individual WT units.

To account for the time dependence of these factors, it is reasonable to assume that the minute-to-minute output fluctuations of WT units and cluster will be somewhat integrated or averaged when compared to actual one second wind fluctuations. Thus, 10 second, 30 second, and 60 second integrated wind fluctuations have been plotted along with the one second wind data, effectively smoothing out the one second wind fluctuations. Table 2-1 summarizes the smoothing effect of integrating the wind fluctuations of the "worst case" 600 second wind fluctuation plot in Appendix E.

Table 2-1

"WORST CASE" WIND FLUCTUATION SUMMARY

	Maximum Wind Fluctuation mph	(m/s)
1. 1 Second Wind Data		
• 10 Second Period	10	(4.5)
2. 10 Second Integrated Wind Fluctuations		
• 10 Second Period	4	(1.8)
• 30 Second Period	6	(2.7)
• 1 Minute Period	10	(4.5)
3. 30 Second Integrated Wind Fluctuations		
• 10 Second Period	3	(1.3)
• 30 Second Period	6	(2.7)
• 1 Minute Period	8	(3.6)
4. 1 Minute Integrated Wind Fluctuations		
• 30 Second Period	3	(1.3)
• 1 Minute Period	5	(2.2)
• 3 Minute Period	6	(2.7)

Although there are little data available with respect to WT output response to actual wind fluctuations, there are data for modeling WT output vs. integrated wind speed change. Figure 2-2 illustrates approximate WT power output vs. wind speed at 30 feet (9.1 m) height for a MOD-2 WT (5, 6). As the integrated wind speed varies from about 8 to 20 mph (3.6 to 9.0 m/s), the MOD-2 WT output level changes at a rate of about 190 kW/mph. As the wind speed varies from 20 to 35 mph (9 to 15.6 m/s), the WT output remains constant. For integrated wind speeds below 8 mph (3.6 m/s) and above 35 mph (15.6 m/s), the WT is shut down.

In order to illustrate the order of magnitude of potential "worst case" wind power plant output fluctuations on a daily basis, an example is presented in Table 2-2 for an 80 MW wind power plant using the Kahuku wind fluctuation data in Table 2-1, the MOD-2 characteristics in Figure 2-2, and the following assumptions:

- One minute integrated wind fluctuation data
- 32 units operating in 8-20 mph (3.6-9.0 m/s) range (fixed pitch)
- 32 units see "worst case" wind fluctuation

Table 2-2

EXAMPLE OF 80 MW WIND POWER PLANT MINUTE-TO-MINUTE OUTPUT CHANGES

Time (Minutes)	"Worst Case" Integrated Wind Fluctuations mph	(m/s)	80 MW Plant Output Change (MW) Coincidence Factor = 1	Coincidence Factor = 0.5
0.5	3	(1.3)	18	9
1	5	(2.2)	30	15
3	6	(2.7)	36	18

HECO FREQUENCY CRITERIA

HECO's nominal system frequency is 60 Hz. However, system frequency constantly fluctuates around this value as the result of continuous changes in load. Under normal conditions, the automatic dispatch system (ADS) returns the system frequency to 60 Hz after load changes. Abnormal system conditions, such as loss of a generating unit, can result in large and sustained deviations from 60 Hz. HECO procedures under such conditions include: changes in control, increase of unit ramping limits, load shedding, and unit separation. This subsection outlines HECO's frequency excursion considerations under normal and abnormal conditions,

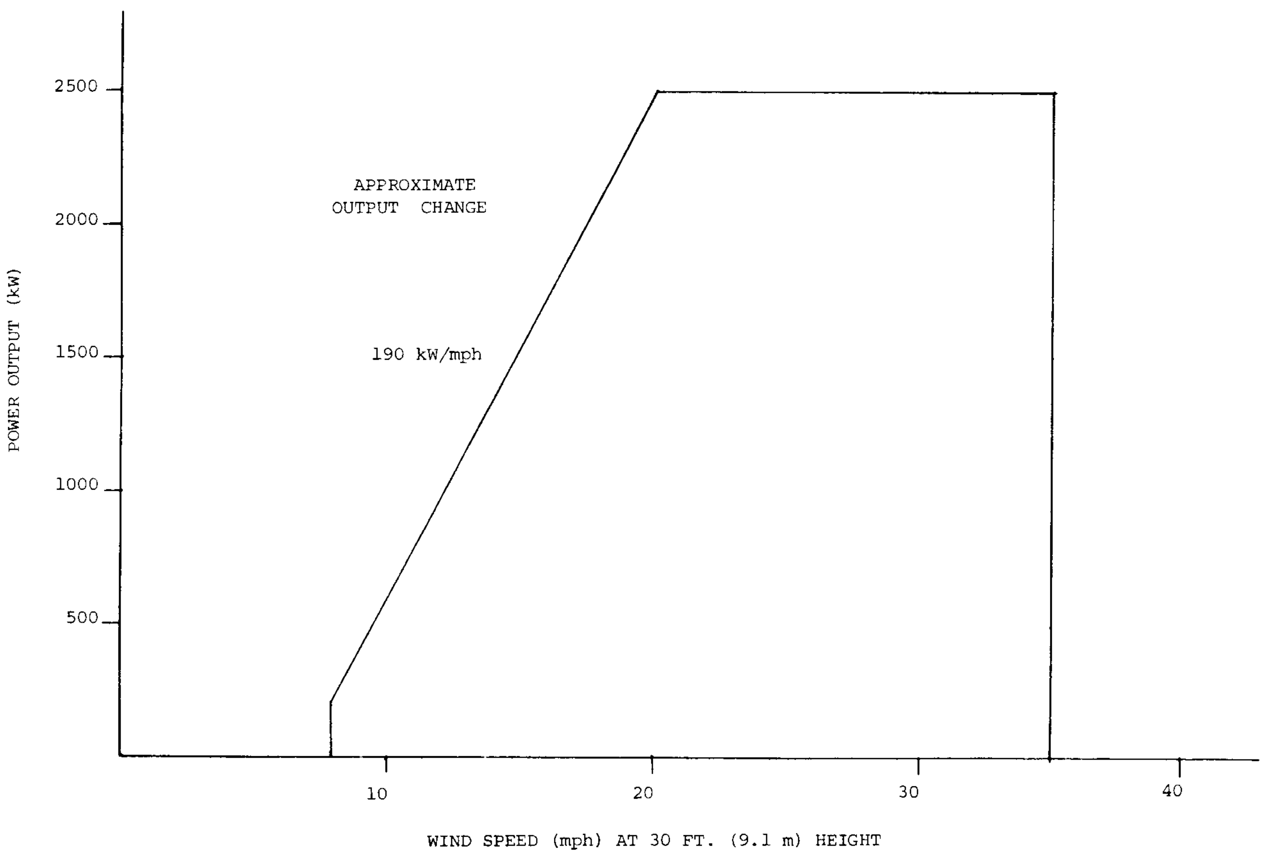

Figure 2-2. Approximate WT (MOD-2) Power Output vs. Wind Speed

and then presents the HECO frequency excursion criteria with and without wind power generation that were used in this study.

HECO frequency recordings under actual day-to-day operating conditions show two different bandwidths depending on whether or not the 10 MW Hawaiian Western Steel (HWS) load, consisting mainly of large arc furnaces, is on-line:

- Without HWS: frequency ranges about ±0.01 Hz around nominal
- With HWS: frequency ranges about ±0.08 Hz around nominal

Abnormal conditions, such as loss of a large generator or load, result in much larger frequency changes. Specific frequency excursion limits (7) trigger the following automatic and manual actions:

- Control - The ADS system transfers from AUTO to LOCAL CONTROL and increases allowable unit ramping rates (in terms of MW change per 3 minutes), when frequency goes below 59.5 Hz or above 60.5 Hz.
- Separation - Generation is automatically or manually separated from the system at 57 Hz when frequency is dropping (to assure retention of auxiliary power.)

For this study HECO proposed frequency excursion criteria of ±0.1 Hz maximum allowed continuously under normal day-to-day operation and up to ±0.4 Hz allowed three times per day. The 0.1 Hz criterion is consistent with HECO's proven operational success with the existing day-to-day ±0.08 Hz excursions with HWS on-line. The 0.4 Hz criterion is consistent with the 0.5 Hz trigger for increasing allowable unit ramping rates.

The 0.1 Hz and 0.4 Hz frequency excursion criteria were used for this study, because these criteria are appropriate for an isolated utility of HECO's size. HECO frequency excursions are an order of magnitude larger than frequency excursions experienced by interconnected utility systems (8).

Section 3

FREQUENCY EXCURSION CALCULATIONS

This section presents the results of an initial assessment of potential system frequency excursions on the HECO system, due to the minute-to-minute changes in wind power generation output. The approach is parametric, since little data on wind fluctuation is available at this time. The magnitude of the maximum allowable combined WT cluster output/load change is calculated for the associated frequency excursion criteria. The frequency excursion results are summarized in two figures - - one for the 0.1 Hz normal maximum deviation from 60 Hz, and one for the 0.4 Hz maximum deviation no more than three times per day.

APPROACH

In this initial assessment a simplified method (9-11) of calculating frequency excursions associated with load and generation changes was used. Frequency excursions from the nominal 60 Hz are the result of short-term (under 30 seconds) mismatches between generation and load. In the usual case, a load fluctuation is followed by appropriate governor action so that generation again balances load. However, due to the delays in governor response and the physical inability of large turbines to change power output quickly, there is a short period of a few seconds where the power mismatch is met only by the stored spinning energy of the turbine-generators. All of the synchronous machines slow down or speed up, lowering or raising frequency, until the governors respond. Experience shows that an uncompensated load change of 1% (8 MW at an 800 MW demand) would result in an initial rate of change in frequency of about 0.5 Hz per second on the isolated HECO system. Interconnected utilities do not experience frequency excursions nearly this great, because of the relatively large amount of spinning energy compared to the load changes.

For isolated utilities, the frequency will continue to diverge from nominal until the governors respond. Then as the generation changes, the load is matched, frequency stops diverging and soon stabilizes at a new value. The frequency excursion calculations in the present initial analysis determine this resulting frequency excursion. A limitation in the simplified methodology is that system behavior in those few seconds until the system has stabilized is not considered.

As described above, after a load change or an equivalent generation change resulting from wind power generation output changes, a utility system will stabilize at a new higher or lower frequency. Supplemental control, in the form of an automatic generation control (AGC) system or the HECO automatic dispatch system (ADS), then returns the system to nominal frequency by increasing or decreasing generation. This section is concerned with the value of the frequency excursion during the period before the relatively slow moving AGC system acts - - say for the first 30 seconds to a minute after the combined WT cluster output/load change.

The method used here for calculating frequency excursions for given power changes is based on the area frequency response characteristic, often referred to as β' (in units of percent of capacity per 0.1 Hz). The area frequency response is the sum of two components, the area governing characteristic and the area load-frequency characteristic.

Area governing is the composite of all the governing characteristics of those units on-line. Figure 3-1 shows a simplified area governing characteristic as line GG. Area governing relates the change in generation of all the units in response to frequency changes, and is often called β_1', in units of percent of capacity per 0.1 Hz. In Figure 3-1 this is shown as a linear relationship, but as shown in Appendix B, this is a simplification.

The area load-frequency characteristic, called β_2' (in units of percent of connected load per 0.1 Hz), describes the magnitude of load changes due to frequency changes. Shown in Figure 3-1 as line LL, β_2' shows how the total synchronous rotating component of the load will change in power required as frequency increases and decreases. Each area differs somewhat in its β_2' depending on the proportion of synchronous machines in the connected load.

Referring again to Figure 3-1, the system would be in equilibrium at nominal frequency, Fo, at point 1. If load increases (or generation decreases) suddenly by two relative units, the governors respond by increasing generation (line GG), and as frequency drops, the power demand of the connected load drops (line LL). The combination of these two factors, numerically defined as β', the area

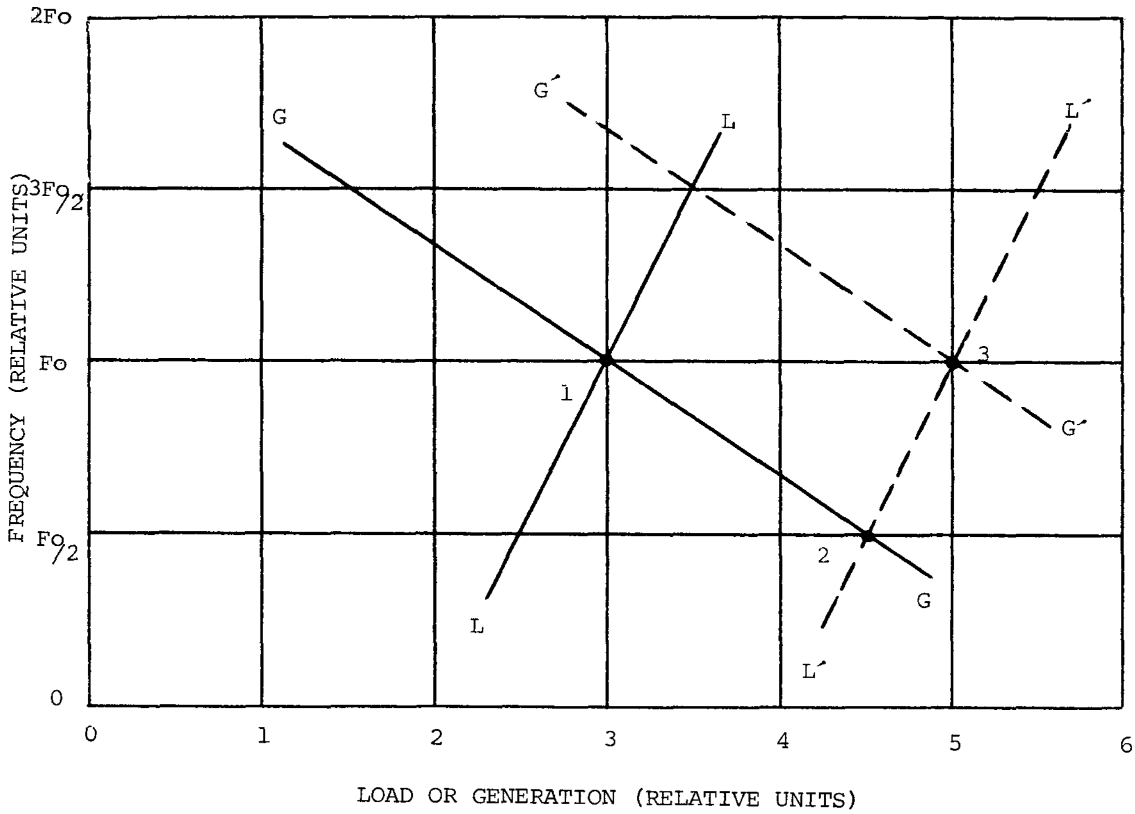

Figure 3-1. Example Area Frequency Response Characteristic. Curves GG and G´G´ are generation governing characteristics. Curves LL and L´L´ are load-frequency characteristics.

frequency response characteristic, puts the system in a new equilibrium state at point 2. Frequency is now depressed to Fo/2. Now supplementary control, i.e. AGC, is used to, in effect, shift the governor controls so that they follow line G´G´. Frequency is then restored to nominal and generation and load are balanced at point 3. As can be seen, the load at point 3 is two relative units greater than the original value at point 1 (reflecting the original sudden change) and the load-frequency characteristic now follows line L´L´.

Results in this section calculated using β', show the allowable load (or generation) change associated with the maximum frequency deviation criteria given in Section 2. These frequency deviations are those that occur in the process of going from point 1 to 2 after any short-term transients and before supplementary control action. In this study, the calculation of β' accounted for the non-linearity of the steam turbine governing characteristic, which is described in Appendix B.

RESULTS

Figure 3-2 illustrates the basic methodology used in presenting the frequency excursion results. Allowable combined WT cluster output/load change is presented as a function of initial HECO system demand for both the 0.1 Hz and 0.4 Hz frequency excursion criteria presented in Section 2. The solid straight lines from the origin present the results, assuming a steam turbine regulation characteristic with a constant 5% droop. The "sawtooth" solid curves illustrate the impact of·accounting for variance in the governing characteristic described in Appendix B. The sawtooth shape is the result of adding generators in HECO's priority order as the system demand increases - - where the worst case is just before another generator is required, and when the spinning reserve is low. The dashed line below each sawtooth approximately connects these "worst cases" and is used in place of the full sawtooth in presenting the frequency excursion results.

Figure 3-3 shows the effect of accounting for the load-frequency component, β_2'. Greater changes in load or generation can be sustained for the same frequency change at any given initial demand when β_2' is included. The frequency excursion results presented in Figures 3-4 and 3-5 include β_2'.

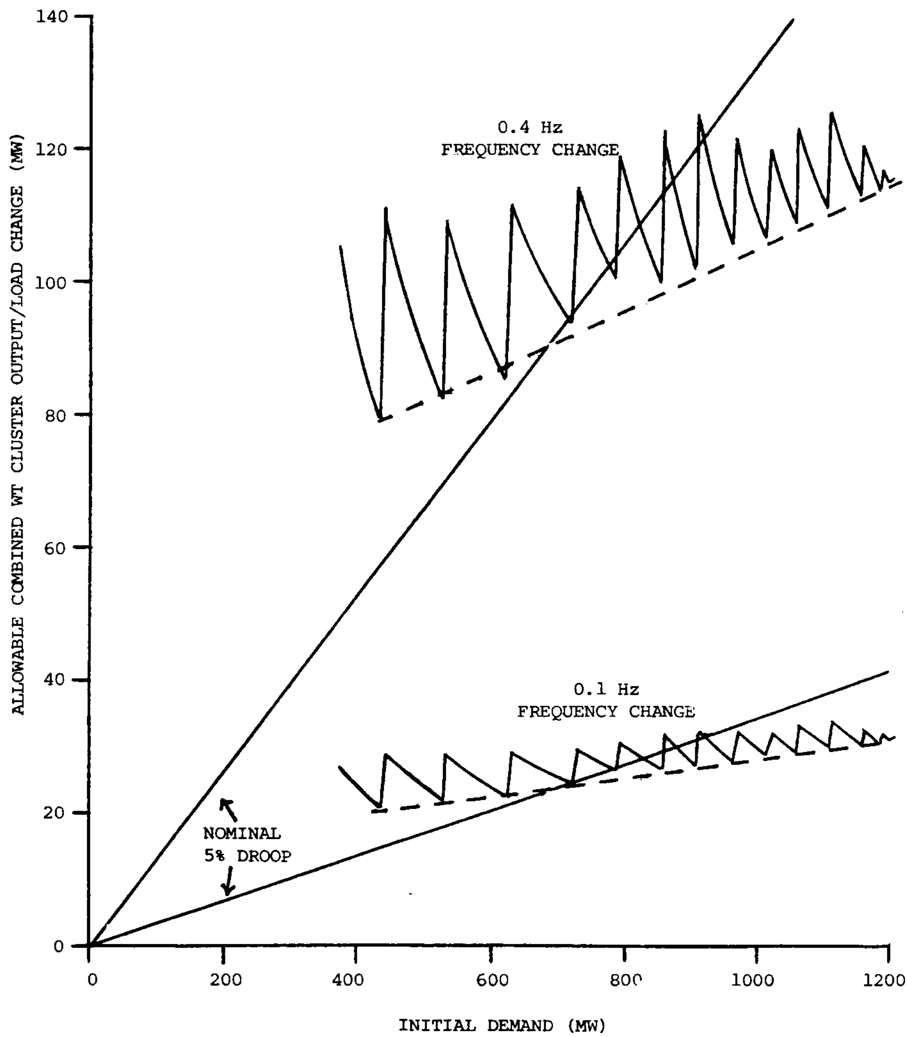

Figure 3-2. Allowable Combined WT Cluster Output/Load Change Due To Governing. A combined WT cluster output/load change means an increase (or decrease) in WT cluster output and simultaneous decrease (or increase) in system demand.

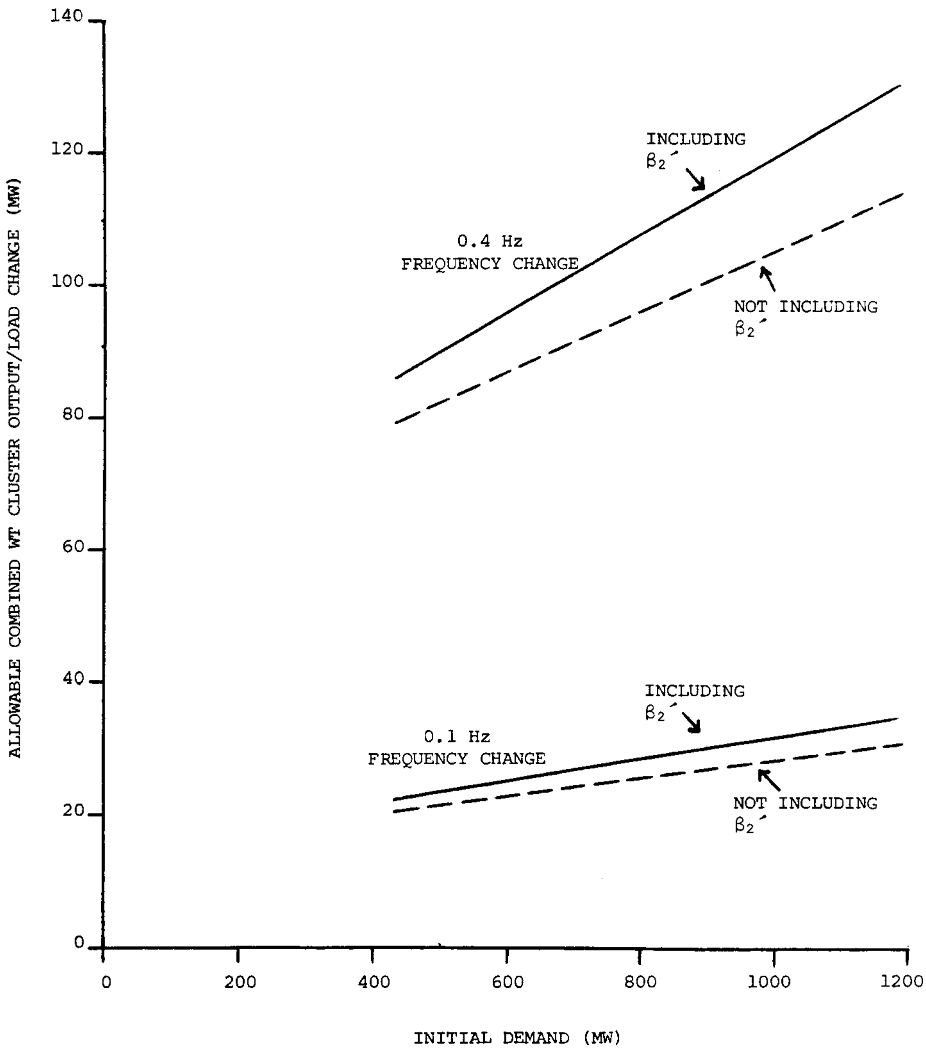

Figure 3-3. Impact of β_2' On Allowable Combined WT Cluster Output/Load Change. A combined WT cluster output/load change means an increase (or decrease) in WT cluster output and simultaneous decrease (or increase) in system demand.

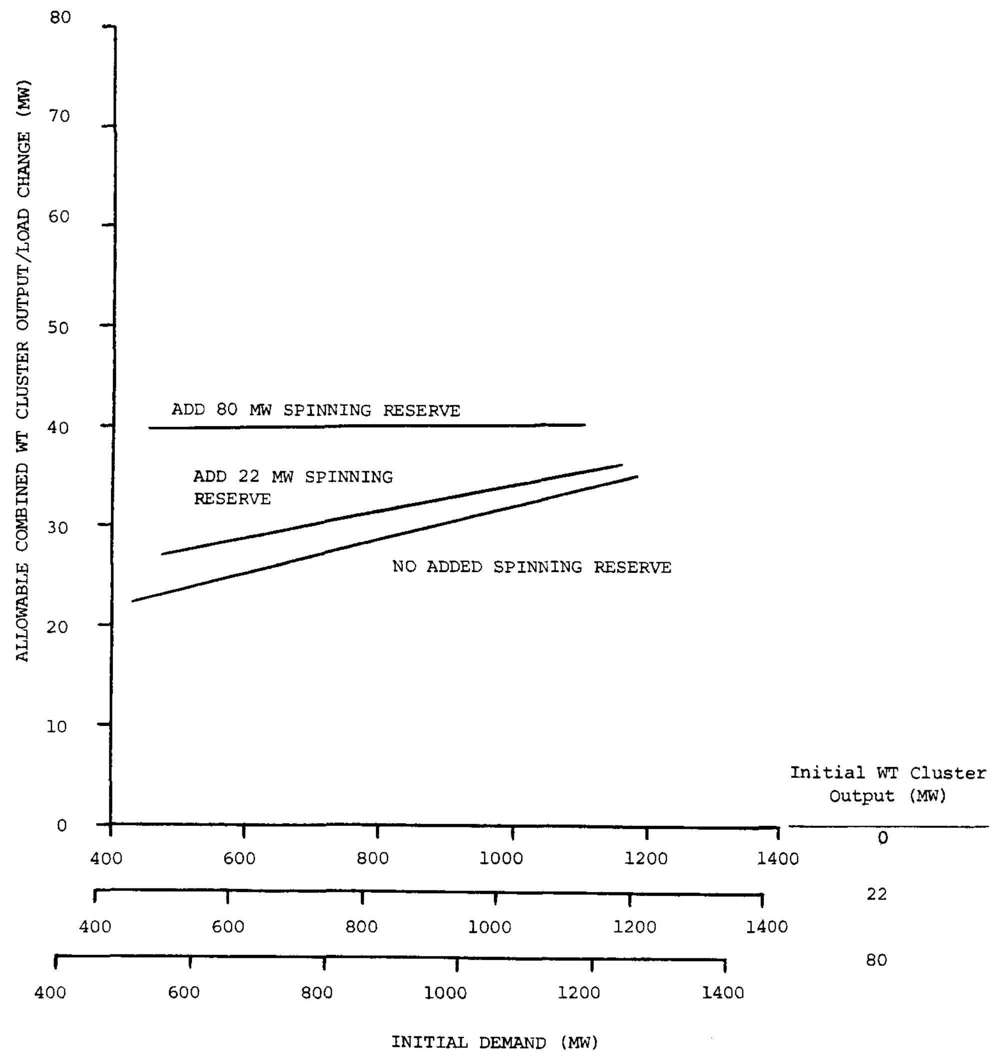

Figure 3-4. Allowable Combined WT Cluster Output/Load Change Corresponding To A 0.1 Hz Frequency Excursion. A combined WT cluster output/ load change means an increase (or decrease) in WT cluster output and simultaneous decrease (or increase) in system demand.

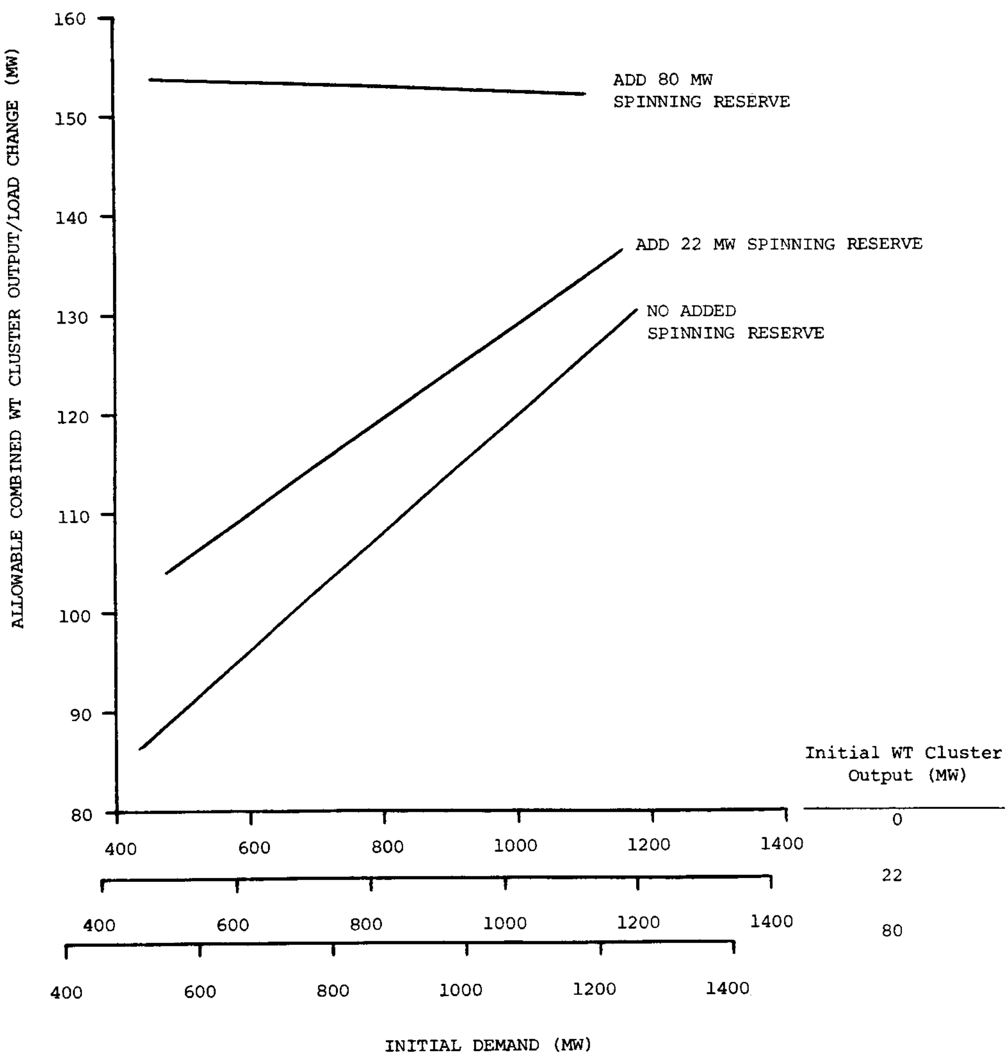

Figure 3-5. Allowable Combined WT Cluster Output/Load Change Corresponding To A 0.4 Hz Frequency Excursion. A combined WT cluster output/ load change means an increase (or decrease) in WT cluster output and simultaneous decrease (or increase) in system demand.

Figure 3-4 presents the results for the 0.1 Hz frequency excursion criterion. The three abscissas shown correspond to the three initial levels of WT cluster output - - 0, 22, and 80 MW. As the initial WT cluster output increases, it displaces conventional generation, decreasing the system's ability to sustain combined WT output/load changes and still meet the frequency criterion. Note that appropriate load changes should be included in determining allowable WT cluster output variations. For example, a sustainable 20 MW total change at 400 MW initial demand may be composed of 20 MW WT output change and no load change, or of a 10 MW WT output increase (or decrease) and simultaneous 10 MW load decrease (or increase). The results indicate that allowable combined WT cluster output and load change will tend to increase with initial demand.

Three levels of spinning reserve are presented. The base case HECO spinning reserve criterion, which varies from about 90 MW at low system demand to 141 MW at higher demand levels, is the "no added spinning reserve" curve. Curves showing the impact of adding 22 and 80 MW of spinning reserve are also presented. The curves show that increasing spinning reserve tends to increase the allowable combined WT cluster/load change.

Figure 3-5 presents the results for the 0.4 Hz criterion. Combined changes of up to 80 MW can always be sustained without exceeding the 0.4 Hz limit. Comparing the two figures, it can be seen that the 0.1 Hz criterion is more critical.

Section 4

MINUTE-TO-MINUTE RAMPING

In this section the ability of the HECO system to sustain wind power generation output changes or load changes on a minute-to-minute basis is examined. Load changes, or generation changes, are first detected and acted upon by the unit governors, which monitor the frequency change and then operate turbine throttles appropriately. Subsequently, HECO's automatic dispatch system (ADS) returns the system to nominal frequency over a period of time. The combined governing and ADS action causes the units under control to ramp up or down to follow the combined WT cluster output/load swings under normal day-to-day operating conditions.

APPROACH

Several factors are involved in the ability of controlled steam generation to ramp or respond to control signals:

- Turbine control and physical characteristics
- Boiler control and physical characteristics
- Plant auxiliary system characteristics
- Operation and maintenance

The control systems have inherent response limits, the turbines have inherent response times due to steam flow travel times (especially reheat), the boilers have limited rates of change in firing rates, and the major auxiliaries have limits to their rates of change. All of these factors when combined can be thought of as giving a spectrum of responses, depending on the duration of the change. For instance, a very fast but limited power change (1% of demand in 0.1 minute) having a 10% per minute rate of change is mostly limited by the turbine and its controls. The boiler uses its stored energy to smooth out any pressure changes until it can respond. A larger power change, such as 10%, may only be sustainable at a lower rate, say 1% per minute - - since boiler dynamics now provide the limit. That is, large changes tend not to be limited by control and process lags, but by limits on maximum pressure and temperature changes. In summary, small percentage power changes can be handled at a high response rate (expressed as percent per minute or MW per minute) while larger percentage changes have associated smaller maximum response rates.

The three factors just discussed, turbine, boiler, and auxiliary characteristics, determine maximum ramping rates and magnitudes that are physically possible for each unit and available under system emergency conditions. HECO has rated its units to generally be able to pick up 60% of their remaining capability within three seconds. This quick load pick-up rating implies response rates in excess of 500% per minute for the three second duration. These rates are not used, or even approached, in day-to-day operation, due to operation and maintenance considerations.

Maintenance cost and reliability considerations limit maximum ramping rates used in normal daily operation (12) to values much smaller than those physically possible. Many mechanisms are responsible for decreased unit reliability and service life due to repeated power output changes at excessive rates. Thermal stresses from temperature differences and temperature changes are the foremost cause. Typically, oil/gas fired drum-type steam units have had allowed sustained ramping rates of 1 to 3% per minute. Some units are rated as high as 5% per minute. Large coal or nuclear units, once-through boiler units, and units designed for baseload operation may be assigned ramping rates of less than 1% per minute. On the other hand, hydro units and gas turbines may have allowed sustained ramping rates exceeding 5% per minute.

In this assessment, the calculations on minute-to-minute ramping were based on HECO's allowed ramping rates for each unit under normal operation (originating from manufacturers' specifications) and priority order, as shown in Table 4-1. The ramping rates are expressed in allowable megawatt change per three minutes. When expressed in units of percent per minute, they range from 1.7% to 2.6% per minute for the steam units, with 3.8% per minute for the two gas turbines. HECO's allowed ramping rates are consistent with the typical values discussed above. These data were combined with HECO supplied economic dispatch data, including spinning reserve, to determine minute-to-minute ramping capability as a function of initial system load level, assuming all units are on control. For generation increases, ramping capability was constrained when units attained rated capacity. For generation decreases, ramping capability was constrained by minimum generation levels.

Table 4-1

HECO GENERATION ALLOWABLE RAMPING RATES FOR A THREE MINUTE INTERVAL

HECO GENERATION PRIORITY ORDER			UNIT CAPACITY (MW)		ALLOWED RAMPING RATE (MW/3 MINUTES)
			Minimum	Rated	
1.	K	6	70	141	7.5
2.	K	5	70	141	7.5
3.	K	4	34	90	6.8
4.	K	3	34	90	6.8
5.	K	2	34	88	6.8
6.	K	1	34	88	6.8
7.	W	7	30	90	6.8
8.	W	8	30	90	6.8
9.	W	5	20	60	4.2
10.	W	6	20	57	4.2
11.	H	9	20	60	4.2
12.	H	8	20	55	4.2
13.	W	4	20	52	1.5
14.	W	3	20	52	2.7
15.	H	7	20	42	2.1
16.	W	9*	5	52	6.0
17.	W	10*	5	52	6.0
18.	H	5	10	23	1.2
19.	W	2	5	18	1.0
20.	W	1	3	8	0.4

*Gas Turbine

Legend:
H Honolulu
K Kahe
W Waiau

Table 4-2 presents an example of minute-to-minute ramping calculations performed. The initial HECO generation dispatch was obtained from HECO supplied economic dispatch criteria. All units are assumed to be on control. For this example, the total system negative ramping capability (generation decrease), corresponding to an allowable combined WT cluster output increase/load decrease, is 55.8 MW. The total system positive ramping capability (generation increase), corresponding to an allowable combined WT cluster output decrease/load increase, is 43.6 MW. As in Section 3, a combined WT cluster output/load change means an increase (or decrease) in WT cluster output and simultaneous decrease (or increase) in system demand.

Table 4-2

EXAMPLE MINUTE-TO-MINUTE RAMPING CALCULATIONS FOR 700 MW HECO DEMAND

INITIAL HECO GENERATION DISPATCH (UNIT)	(MW)	RAMPING CAPABILITY/3 MINUTES INCREASE (MW)	DECREASE (MW)
K 6	107	7.5	7.5
K 5	107	7.5	7.5
K 4	89	1.0	6.8
K 3	67	6.8	6.8
K 2	85	3.0	6.8
K 1	88	0.0	6.8
W 7	69	6.8	6.8
W 8	68	6.8	6.8
W 5	20	4.2	0.0
TOTAL	700	43.6	55.8

To illustrate how the entries in Table 4-2 were obtained, consider the column labeled "INCREASE." The column entry for any particular unit is its maximum allowable ramp in a three minute interval (from Table 4-1), unless the unit's rating has been reached, in which case all remaining power up to its rating is entered. An entirely analogous treatment applies for the column labeled "DECREASE" with unit minimum power taking the role of unit rating.

RESULTS

Figure 4-1 presents the allowable combined WT cluster output/load change in a three minute period, as a function of initial system demand, assuming HECO allowed ramping rates. The impact of different initial WT cluster outputs of 0, 22, and 80 MW is also considered in this figure. The solid line presents the allowable combined WT cluster output increase/load decrease, and the dashed line presents the allowable combined WT cluster output decrease/load increase. In general, the allowable combined WT cluster output decrease/load increase over a three minute period (corresponding to a HECO generation system increase) is the limiting condition for HECO minute-to-minute criteria.

Figures 4-2 and 4-3 illustrate the impact on allowable combined WT cluster output/load change in a three minute period of increasing the HECO spinning reserve criterion by 80 MW. Comparing the results of an 80 MW reserve increase, the allowable combined WT cluster output decrease/load increase is the limiting condition at high demand levels. However, combined WT cluster output increase/load decrease becomes the limiting condition at low demand levels.

Figures 4-4 and 4-5 illustrate the impact on allowable combined WT cluster output/load change in a three minute period of increasing allowable HECO generation ramping rates by 50%. Figures 4-6 and 4-7 illustrate the impact of doubling allowable HECO generation ramping rates. The results are plotted both for HECO's specified spinning reserve and for HECO's specified spinning reserve plus 80 MW.

The curves of allowable combined WT cluster output increase/load decrease shown in Figures 4-1, 4-2, 4-4, and 4-6 are indicative of three minute HECO generation down-ramping ability. All these figures show similarly shaped plots with increasing allowable combined WT/load change as the initial HECO demand increases. The HECO generation three minute down-ramping ability increases as allowable ramping rates are increased by 50 and 100 percent, as would be expected, but not in direct proportion due to unit minimum loads. Increasing spinning reserve, as shown by the dashed lines, has little effect. In fact, this actually decreases the ramping ability at some initial demands, because many of the on-line generators are operating near minimum levels and have little ability to ramp down.

The curves of allowable combined WT cluster output decrease/load increase shown in Figures 4-1, 4-3, 4-5, and 4-7 are indicative of three minute HECO generation

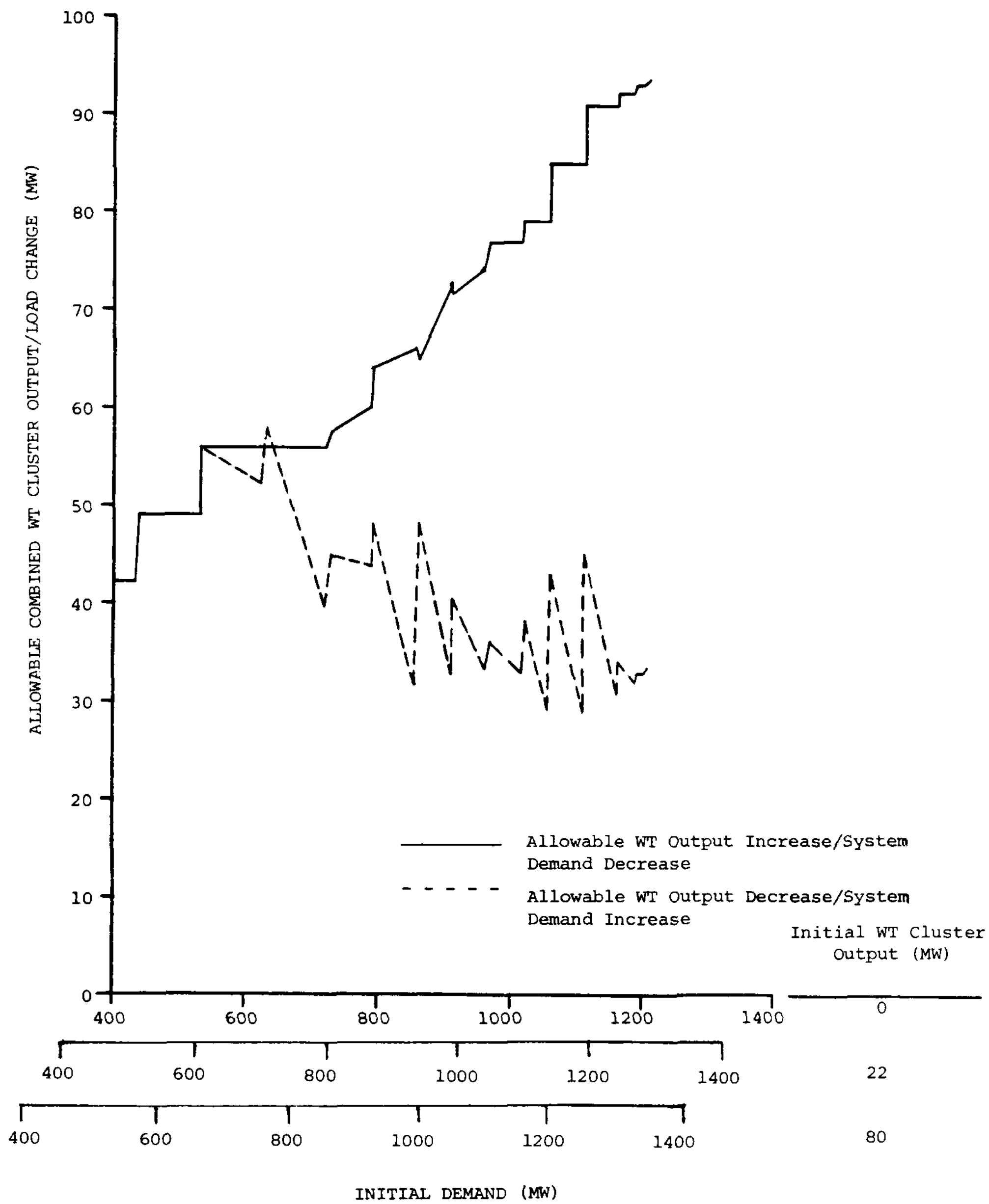

Figure 4-1. Allowable Combined WT Cluster Output/Load Change In Three Minutes Using Allowable Three Minute HECO Generation Ramping Criteria

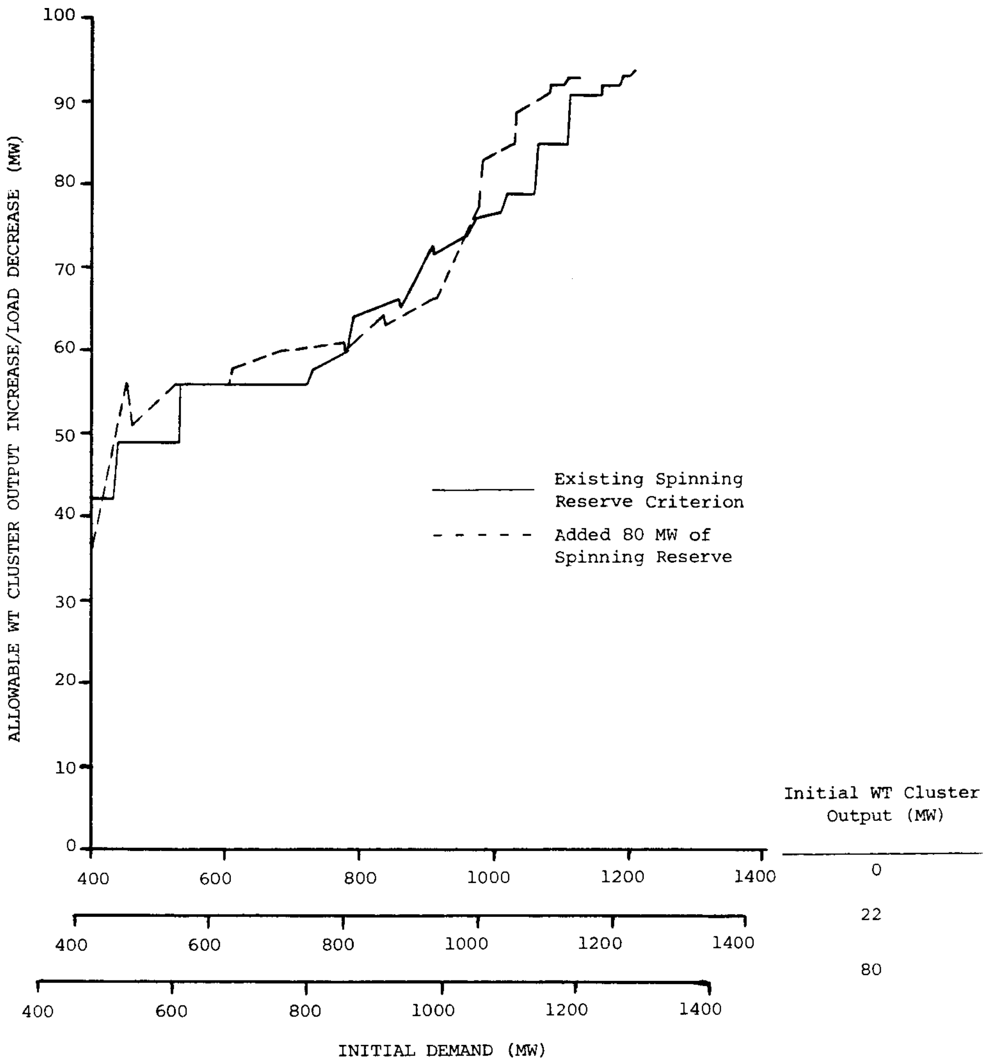

Figure 4-2. Impact Of Increasing HECO Spinning Reserve Criteria By 80 MW On Allowable Combined WT Cluster Output Increase/Load Decrease In Three Minutes

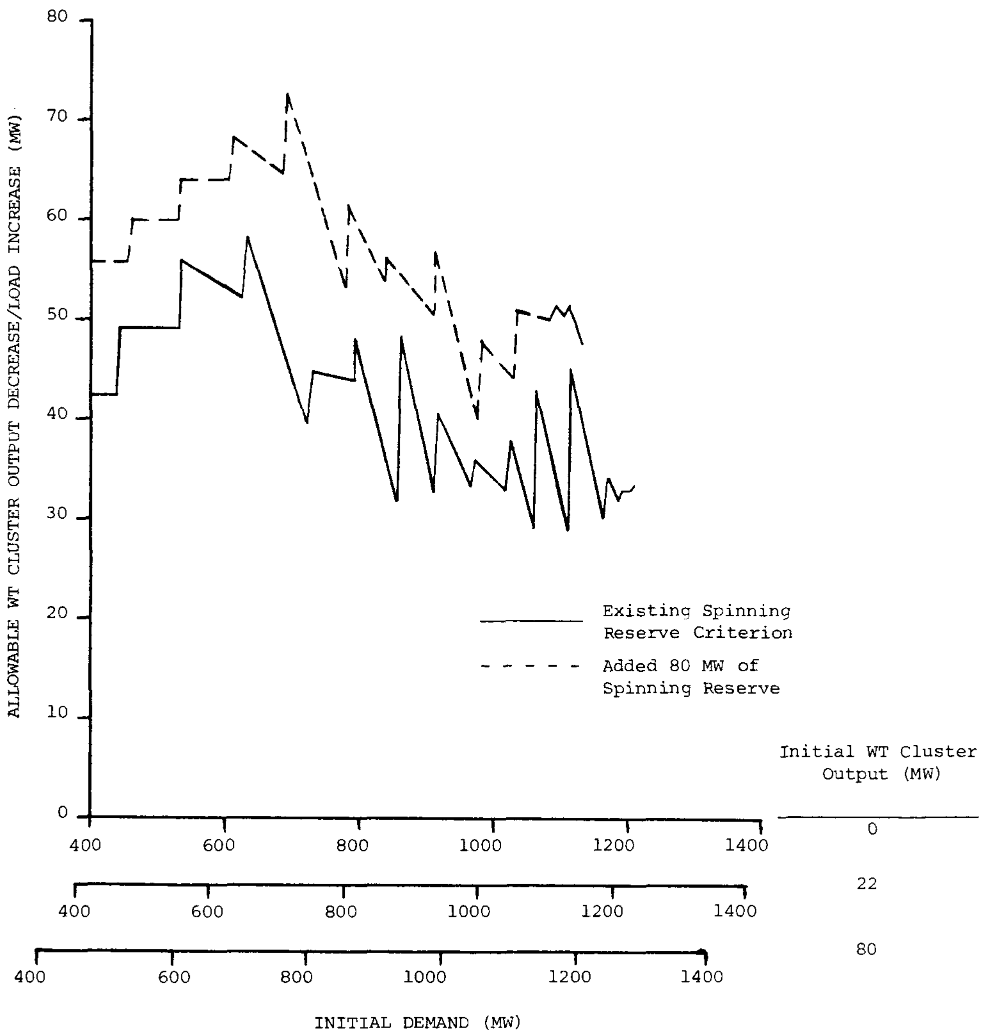

Figure 4-3. Impact Of Increasing HECO Spinning Reserve Criteria By 80 MW On Allowable Combined WT Cluster Output Decrease/Load Increase In Three Minutes

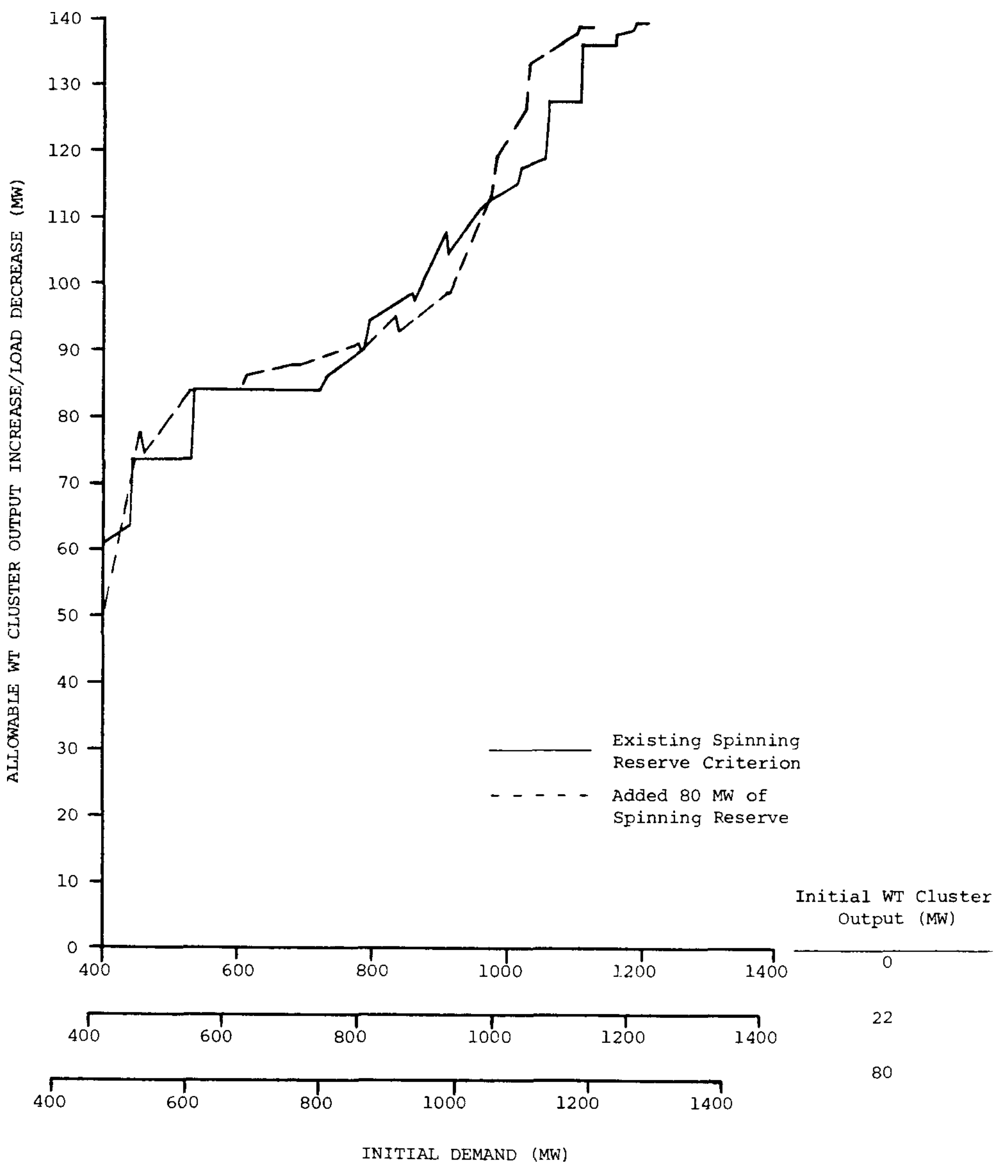

Figure 4-4. Allowable Combined WT Cluster Output Increase/Load Decrease In Three Minutes With Allowable HECO Generation Ramping Rates Increased By 50%

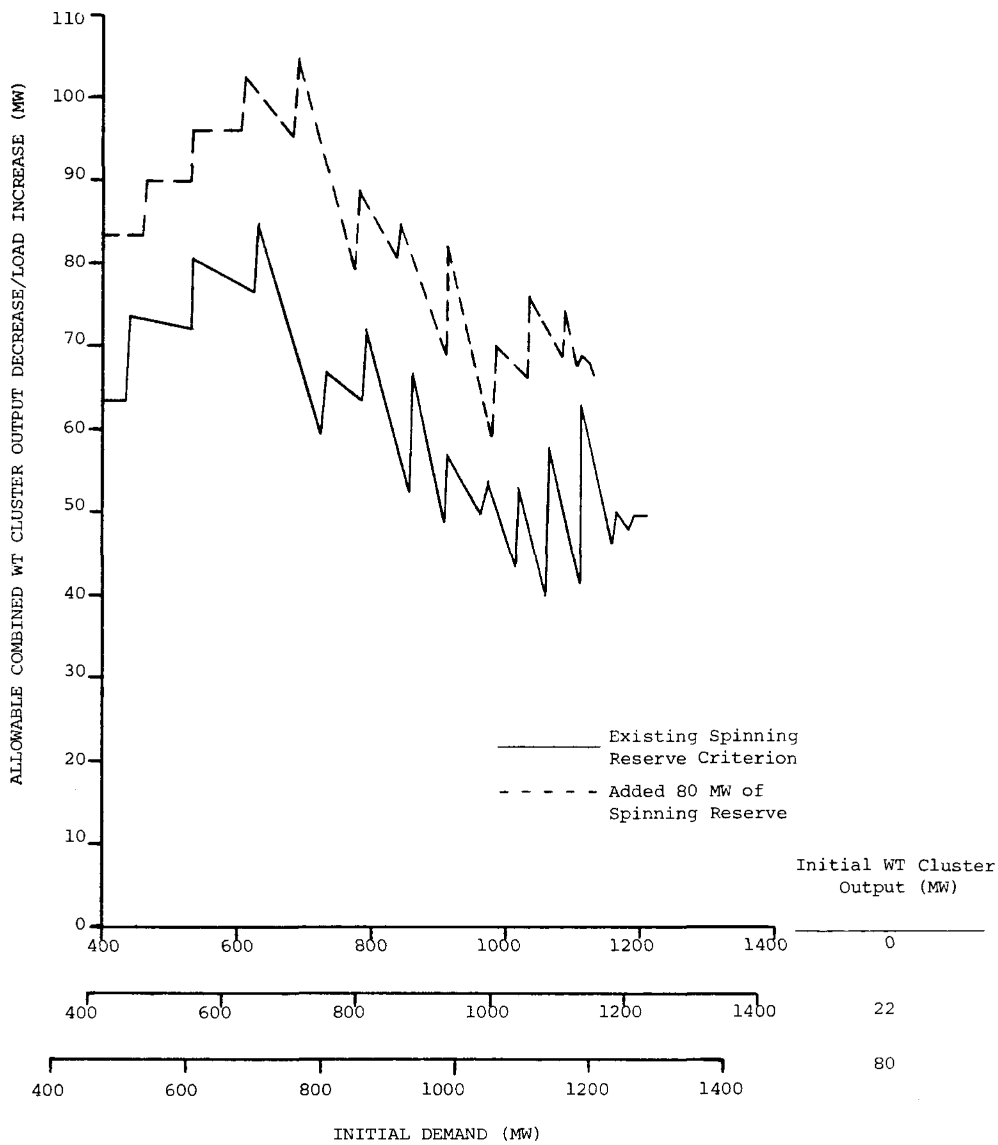

Figure 4-5. Allowable Combined WT Cluster Output Decrease/Load Increase In Three Minutes With Allowable HECO Generation Ramping Rates Increased By 50%

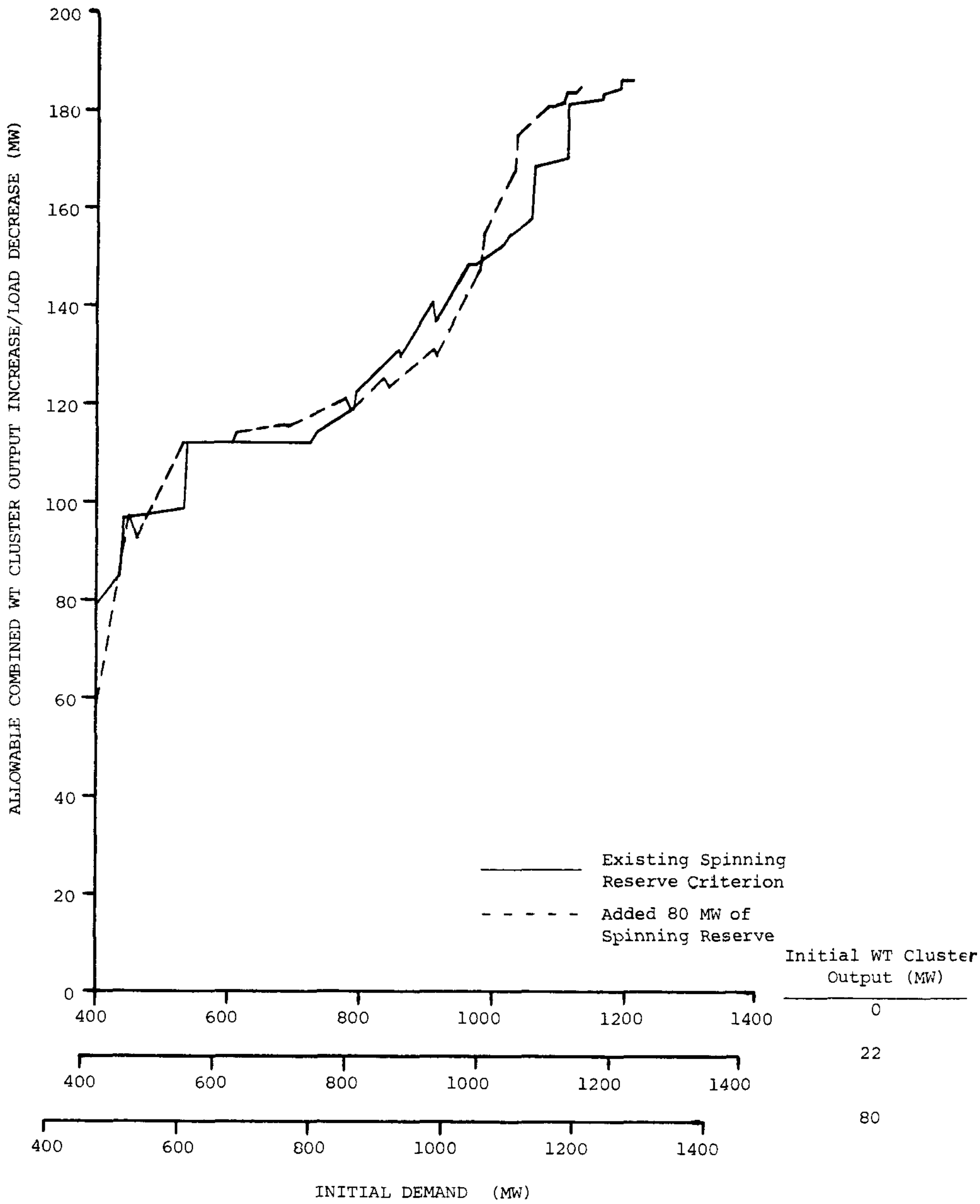

Figure 4-6. Allowable Combined WT Cluster Output Increase/Load Decrease In Three Minutes With Allowable HECO Generation Ramping Rates Doubled

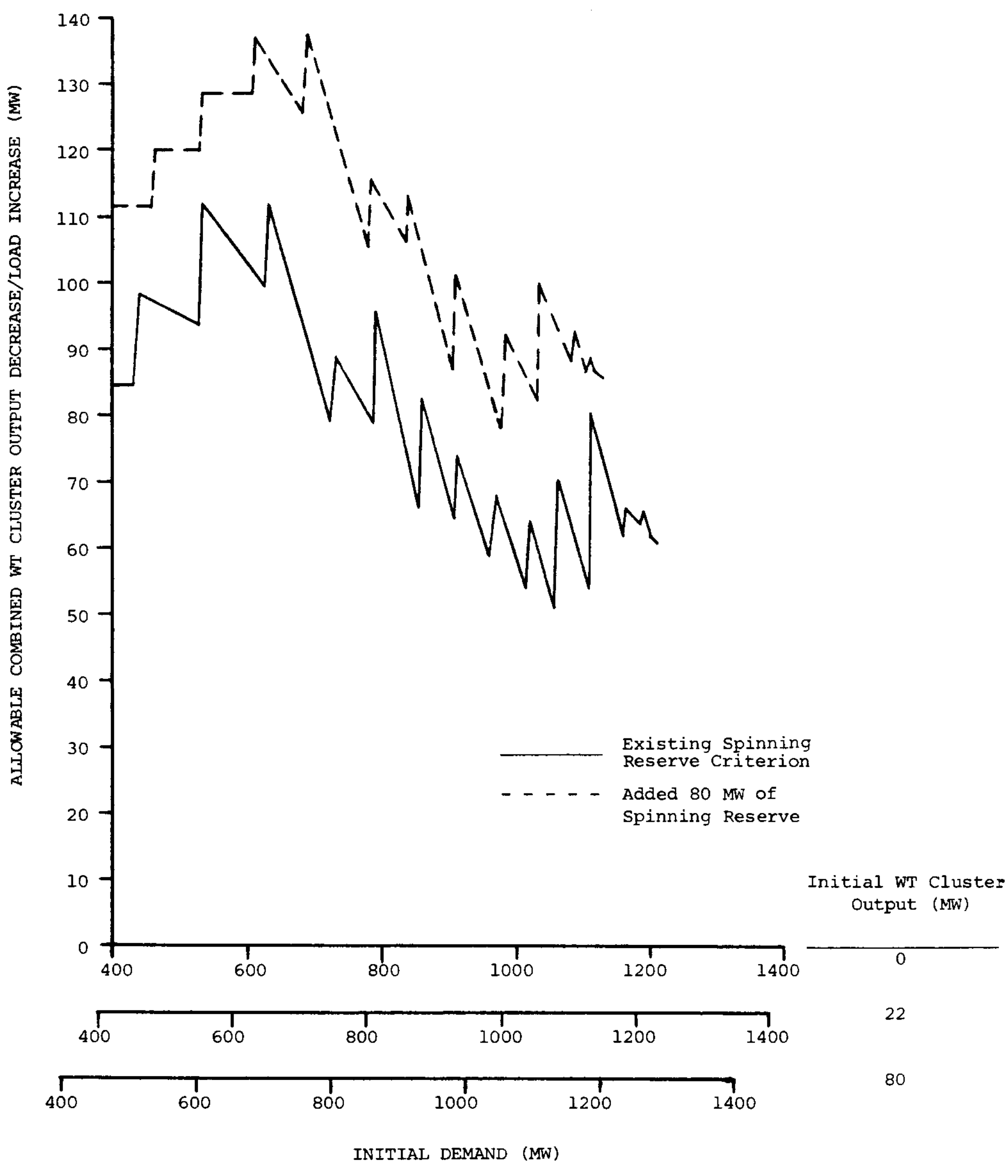

Figure 4-7. Allowable Combined WT Cluster Output Decrease/Load Increase In Three Minutes With Allowable HECO Generation Ramping Rates Doubled

up-ramping ability. These curves all have the same general shape: initial high allowable combined WT output/load change, decreasing along a sawtooth as initial HECO system demand increases. This characteristic remains the same for increased spinning reserve, as shown by the dashed lines in Figures 4-3, 4-5, and 4-7. The figures show that allowable combined WT cluster output decrease/load increase is significantly greater with increased spinning reserve. The effect of increased spinning reserve is to shift the curves up in an almost uniform manner.

Table 4-3 summarizes "worst case" allowable combined WT cluster output/load change over the total range of HECO system demand for the minute-to-minute ramping conditions described in Figures 4-1 through 4-7. "Worst case" allowable combined WT output increase/load decrease (and corresponding generation decrease) always occurs at low initial demand. "Worst case" allowable combined WT output decrease/load increase (and corresponding generation increase) always occurs at high initial system demand. For the HECO spinning reserve criterion, the "worst case" allowable combined WT cluster output/load change is smaller and more critical for HECO minute-to-minute generation increase (up-ramping) then for generation decrease (down-ramping). When the spinning reserve is increased by 80 MW, the opposite is the case.

Table 4-3

"WORST CASE" ALLOWABLE COMBINED WT CLUSTER OUTPUT/LOAD CHANGE

OPERATING CONDITIONS AND ASSUMPTIONS		HECO ALLOWED RAMPING (MW)	HECO RAMPING PLUS 50% (MW)	HECO RAMPING PLUS 100% (MW)
Generation Decrease	Existing Reserve Criterion	42	63	79
Generation Decrease	Added 80 MW of Reserve	36	50	57
Generation Increase	Existing Reserve Criterion	29	40	51
Generation Increase	Added 80 MW of Reserve	40	59	78

Several methods are available to handle this potential situation of inadequate system ramping ability to meet normal combined WT cluster output and load changes. A simple limitátion could be placed on total installed wind power plants - - a "penetration" limit. Yet, higher penetrations would be possible by limiting use of the wind power plants under certain conditions. Low system demand levels are severe conditions for both up-ramping and down-ramping and WT cluster use could be curtailed under these conditions if necessary. An important point here is that up-ramping is the limiting case for all but the lowest demand levels. Up-ramping is required to compensate wind power decreases.

Several methods of increasing normal minute-to-minute generation ramping ability, if necessary, are suggested by the figures and Table 4-3. Increasing spinning reserve improves up-ramping ability. Increasing allowed unit ramping rates generally improves allowable combined WT cluster output/load change, but not in direct proportion. For example, a 50% increase in ramping rate increased allowable combined WT cluster output/load change from 29 to 40 MW, a 38% increase. It may be possible with testing and improved control algorithms to increase the allowed generation day-to-day ramping rates on thermal units without adverse impact. Some equipment changes, particularly in control, instrumentation, and auxiliaries, may be indicated as a low cost way to improve unit response.

Another method for improving the generation system ramping ability involves changes in the day-to-day dispatching. It was noted previously that a principal limitation on up-ramping is the units unable to ramp because they are already at or near maximum output. Dispatching units further below their maximum output would greatly improve the total system up-ramping ability. The increased cost resulting from the non-optimal generation dispatch could be offset by increased ability to use wind power. It may be possible to alter the dispatching on a day-to-day basis to account for expected wind velocities and variability.

INTERCONNECTED OPERATION

This study involved an isolated utility. As stated in Section 3, frequency excursions will be much smaller for interconnected utilities. Thus, day-to-day frequency excursions are not expected to be a dynamic problem for interconnected utilities. However, minute-to-minute ramping considerations may well be important when analyzing possible large wind power penetration levels. There are two possible areas of concern: tie-line overload and meeting interconnection control criteria.

It is possible that a utility with large wind power penetration could experience a large drop in wind power, causing tie-line overflows. This potential problem is expected to be less severe than meeting interconnection control criteria. In any event, it could probably be solved by adding tie-line capacity as needed.

The major potential problem area is with interconnection control criteria, as promulgated by NAPSIC, NERC, and individual power pools. The most basic of these criteria is that area control error (ACE) must cross zero at least once every ten minutes. The potential problem is this: Given a large and sustained wind power generation change occurring in less than ten minutes, can the other units on control ramp sufficiently so that ACE will cross zero within a ten minute period? This may not be a hard and fast requirement, in that control performance has often historically been enforced only by peer pressure. However, some power pools impose penalties for poor control performance and this practice may spread.

Daily operation of interconnected utility systems is significantly different than the daily operation practices of the isolated HECO system, resulting in significantly different allowable combined WT cluster output/load change on a minute-to-minute basis. Some of the potential differences are as follows:

- Only a fraction of the units may be on control, the rest being baseloaded. This is especially significant for low system demand at night and on weekends, and for utilities having a high proportion of baseload generation.
- The utility may have a mix of units with minimal response capability. These include units specifically designed for baseload operation, once-through boiler units, coal plants, and nuclear plants. In addition, interconnected utilities generally install larger units.
- An interconnected utility may have relatively low spinning reserves, compared to HECO, limiting ability of generation to up-ramp.

In conclusion, minute-to-minute ramping is an important consideration in determining potential limitations to wind power penetration. These minute-to-minute constraints are expected to apply to both isolated and some interconnected utilities. The basic consideration throughout has been not whether a utility can sustain large wind power fluctuations, but what magnitude of combined WT cluster output/load changes can be sustained while meeting reasonable maintenance, reliability, and control criteria under normal day-to-day operation. This consideration has been found to be a complex function of many variables including: spinning reserve levels, generation mix at different times, control operation, and individual unit response characteristics.

Section 5

SHORT-TERM STABILITY

This section presents the results of short-term stability calculations performed on the HECO system. The purpose of the short-term stability analysis was to perform an initial assessment of the relative stability of the HECO system with and without wind turbines during very severe system disturbances, which are expected to occur infrequently, if at all.

APPROACH

A power system is said to be in a condition of transient stability (13) with respect to a given disturbance if, following this disturbance, it returns to a condition of steady-state operation. In the case of an isolated system (such as the HECO system), if a generator is tripped, the system frequency after returning to steady-state would be lower than the original steady-state system frequency of 60 Hz. The rotor angles of the machines can no longer be compared to the reference angle for the machines which is based on 60 Hz. Hence, the relative rotor angles of the machines must be compared to determine if the system remains in synchronism.

Transient stability analysis is performed to compare the magnitude of fluctuations in relative rotor angles of the machines. In this study these fluctuations were studied for a short time interval (up to 3 seconds) after the disturbance. This time frame for dynamic assessment is compatible with the state of the art in WT dynamic modeling. Due to this short time frame, no modeling of automatic generation control or other slower acting controls was required for the transient stability analysis.

An initial set of 10 stability cases was identified early in the project. Based upon results for these 10 cases and concerns of HECO, other specific cases were identified and analyzed. One such special case will be discussed later. These initial 10 cases were envisioned to cover a sufficiently broad range of load conditions and system disturbances to identify any potential transient stability problems that might arise from the installation and operation of a large WT cluster on the HECO system.

Transient stability was analyzed under three different system configurations:

1. HECO system with no wind machines (base case)
2. HECO system with an 80 MW WT cluster at Kahuku (80 MW wind)
3. HECO system with a 22 MW WT cluster at Kahuku (22 MW wind)

The first of these was analyzed to establish the HECO system stability characteristics prior to the consideration of wind power systems. The second configuration includes the incorporation of a planned 80 MW WT cluster into the HECO system. The third is a potential interim configuration in which the initial installation of 22 MW of wind turbines is considered.

Each of these configurations was studied for two load levels, projected peak loads for 1985 and projected low loads for 1985. The base case HECO system configuration projected for 1985 is given in Appendix A. The system configuration for the 80 MW wind case is the same as for the base case, except for a 138 kV line connecting the 80 MW WT cluster to the bus at Wahiawa, as shown in Appendix A. In the third configuration, a 22 MW WT cluster at Kahuku is connected to the Wahiawa bus through the existing 46 kV network, as shown in Appendix A.

The transient stability analysis for these configurations, and both light and peak load levels, was performed for two severe disturbances. The first disturbance was the loss of the largest generating unit on the system in all three configurations, and the other was the loss of all the wind power generation simultaneously in configurations 2 and 3. These scenarios were decided upon to establish whether the system would be stable without wind power generation, and if so, then to study if it would remain stable with the 80 MW and 22 MW wind power plants installed for the same disturbance. Also, these latter configurations were studied to see whether the system would be stable if all wind power generation was lost in each case.

The conventional machine representation used to perform this analysis is described in Appendix C. Machine data obtained from HECO was initially supplemented by typical data from EPRI EM-285, "Synthetic Electric Utility Systems for Evaluating Advanced Technologies," (3) and typical IEEE data (14).

The response of this typical representation for the governor-turbine system was found to be slower than the HECO experience with unit response to the system frequency changes. The governor system time constants were adjusted to match the unit model response to that of the units on the HECO system. It was also found that the system voltages increase unrealistically with the typical representation for the exciter system. To match the exciter response to the voltage fluctuations actually experienced by HECO under similar system conditions, the exciter system representation was modified. The final parameters used for the HECO generation units in this analysis are given in Appendix C.

The WT cluster was modeled as a single equivalent machine, having two masses connected through a spring. The masses represent the wind turbine inertia and the generator inertia, and the spring represents the quill shaft. That was, in turn, represented on the computer as two electrical machines connected through a transmission line. An analog WT dynamic model suitable for an initial transient stability analysis was derived from the two-mass model. The model and the computer representation are described in detail in Appendix D. At this time there is little experience with WT dynamic performance models. The WT dynamic model was based on "best available data." Future studies should use improved WT dynamic models as they become available. For this study, constant impedence load representation is used in all the stability cases.

Under these assumptions, the transient stability runs were made using a version of the Philadelphia Electric Company transient stability program. The swing curves were plotted for the various rotor angles on the system. These swing curves were studied to analyze the system stability.

RESULTS

The following observations were made from these runs. For peak load conditions, in all cases the system frequency slipped to 59 Hz in about 2 seconds after the disturbance. The system frequency then started to increase about 3 seconds after the disturbance. The frequency curve for the base case peak load condition is shown in Figure 5-1. The shape of this frequency curve is typical for all stability cases studied under both peak and low load conditions.

The rotor angles of all the machines drop at a very fast rate relative to the reference angle. This is because the reference angle is determined by a fictitious

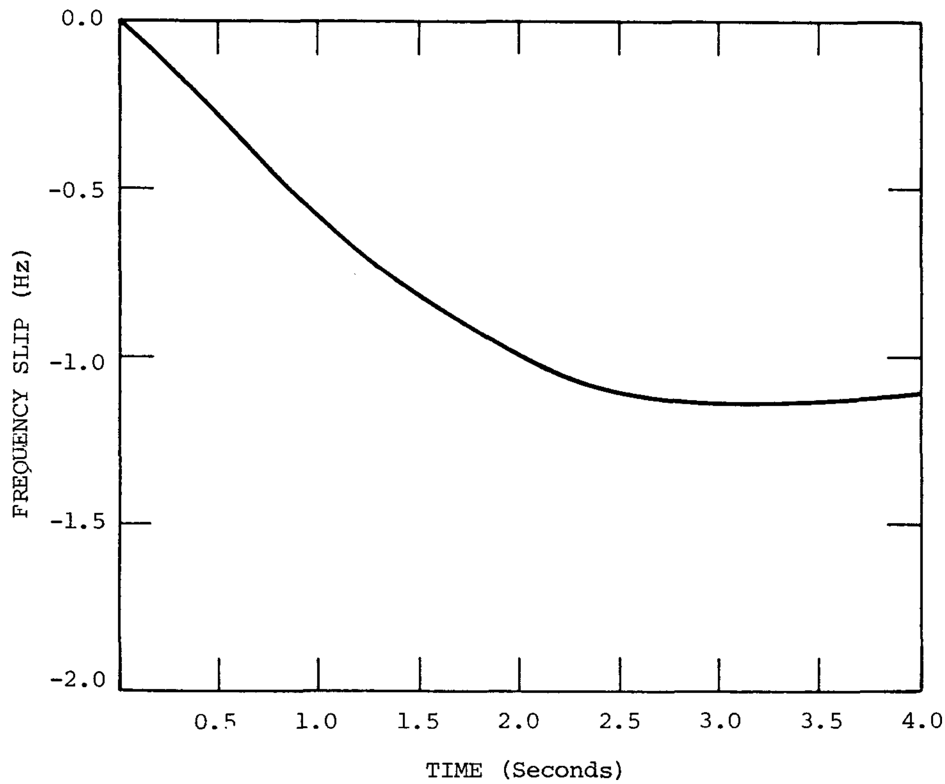

Figure 5-1. Base Case (No Wind) Peak Load Generator Frequency Slip For Kahe 5 When Kahe 6 Is Tripped

rotor running at synchronous speed. However, the rotor angles of the machines relative to each other do not change very much. The plots shown in Figure 5-2 and Figure 5-3 are typical for all cases.

The system was stable in the transient state under all the conditions studied. The result is what one would expect for a concentrated system, like that of HECO, having short transmission lines with very small reactances.

Under the peak load condition the fluctuations in the relative rotor angles due to tripping of the largest HECO unit are more prominent than the fluctuations due to complete loss of the wind power plant. Also, under the low load condition, tripping of the largest generating unit causes the maximum fluctuation in the relative rotor angles.

Fluctuation in the rotor angle of the machine representing the turbine part of the WT cluster equivalent relative to the rotor angle of the machine representing the generator part is less than 20 degrees. The change in power delivered by the WT cluster during the disturbance is negligible. Thus, the linearized two machine model is a valid representation of the WT cluster for cases studied. For future assessments, it must be noted that this model will not be valid if the power delivered by the WT cluster during the disturbance changes be a non-negligible amount. A small change in power delivered by the WT cluster would cause a very large change in the relative angle between the turbine mass equivalent and the generator mass equivalent, and hence, the linearized two machine model being used here would not be valid.

Representative swing curves for these 10 stability runs are given in Appendix F. For each run, the swing curves were plotted for two different time frames, 0 to 0.5 seconds and 0 to 3.0 seconds, to show both the short-term transient stability and the long-term transient stability. The swing curves are plotted in terms of absolute rotor angles. Analysis of the swing curves leads to the following conclusions.

The HECO system is a very strongly coupled system and is stable after the sudden loss of its largest generating unit under both the peak load and the low load conditions. The HECO system with the WT cluster at the Kahuku site is stable for all the disturbances described earlier.

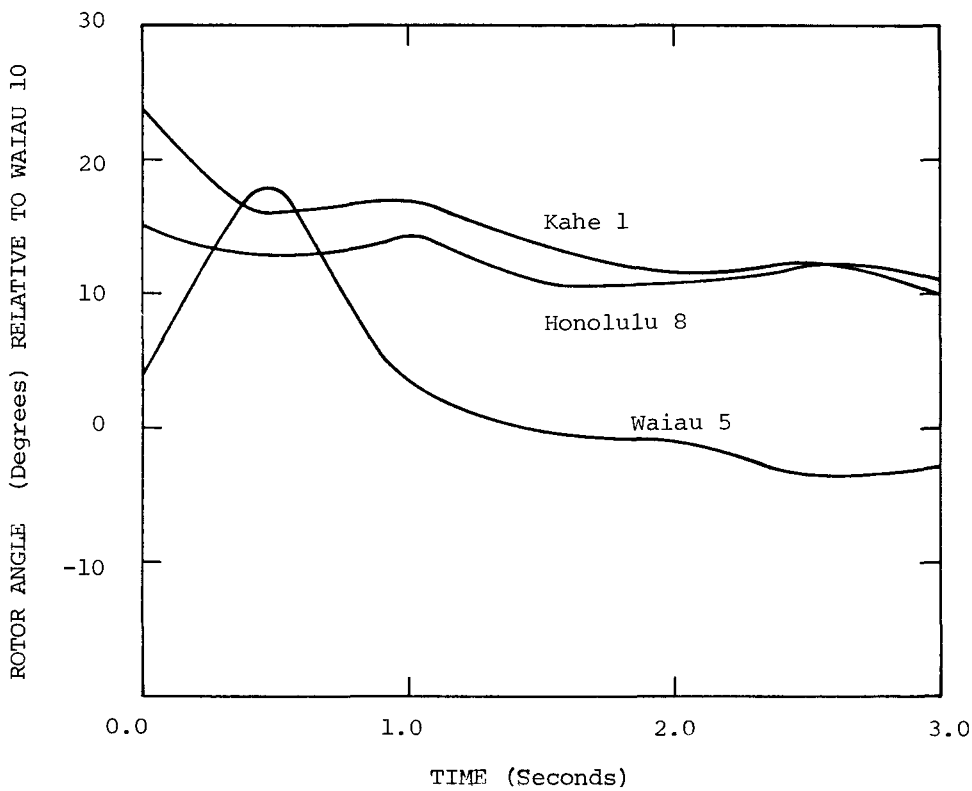

Figure 5-2. Generation Swing Curves For Tripping 80 MW WT Cluster At Peak Load

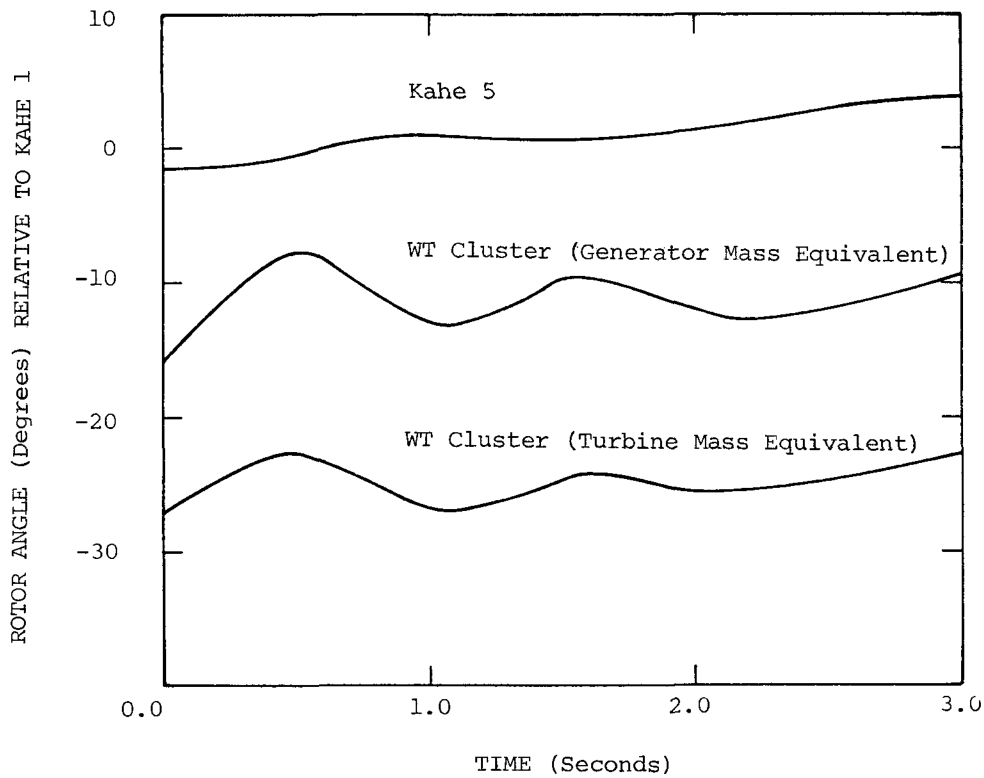

Figure 5-3. Generation Swing Curves For Tripping Kahe 6 At Low Load

A special additional case under the peak load condition with the 80 MW WT cluster configuration was suggested by HECO for this study. This case involves isolation of the Ceip load and Kahe power plant from the rest of the system and then tripping loads at Pukele (186 MW) and Koolau (179 MW) when the frequency slips to 59.5 Hz. Also, when the frequency slips to 57.9 Hz, the loads at Wahiawa (108 MW), Waiau (41 MW), and Honolulu (39 MW) are tripped.

The analog WT model described in Appendix D was used to represent the WT cluster for this stability case. When Kahe power plant is separated from the rest of the HECO system, the frequency of the system (without Kahe generation) drops very rapidly. After 0.2 seconds of the separation, the system frequency drops to about 59.5 Hz. At this point 186 MW of Pukele and 179 MW of Koolau loads are shed. The power factor of the remaining load at both buses is the same as the power factor before the Kahe trip. This slows the drop in frequency, but the system frequency still keeps slipping down. About 2.0 seconds after the separation of Kahe plant from the rest of the system, the system frequency drops down to 57.9 Hz. At this point, 108 MW of Wahiawa, 41 MW of Waiau, and 39 MW of Honolulu (bus 33) loads are shed. The power factor of the remaining load at these buses is kept the same as before the separation of the Kahe plant.

It was found that the maximum drop in the system voltages was less than 6 percent of the initial voltage levels. The system voltages improved after the load shedding at Pukele and Koolau substations.

The system itself was found to be operating in synchronism. The WT cluster generator equivalent was found to be the most active, because the generator shaft has very small inertia compared to the shaft inertia of a conventional machine. In this run, large rotor angle fluctuation relative to the WT turbine equivalent was observed, which tends to reduce the WT model accuracy. Although the wind machine equivalent was the most active, it still remained in synchronism with the rest of the system.

The system frequency dropped down to 57.9 Hz at about 2.0 seconds after the separation of the Kahe plant from the rest of the system. The system frequency then started to pick up after the loads at Wahiawa, Waiau, and Honolulu were shed. The system frequency picked up to 59 Hz and was still improving at about 3.2 seconds after shedding these loads. The run was terminated at this point.

Hence, the HECO system for the above special case was found to be stable. The system frequency would eventually return to normal after shedding the above-mentioned loads.

Section 6

CONCLUSIONS AND RECOMMENDATIONS

This section presents a summary of conclusions and recommendations determined during the performance of this project - - an initial assessment of potential wind power generation dynamic impacts on electric utility systems.

CONCLUSIONS

Some general conclusions and observations are as follows:

- Utility system dynamic impacts may limit the potential penetration of wind turbines.
- Operating restrictions on large wind power plants due to dynamic impacts will tend to reduce their annual energy output. Hence, annual energy projections for large wind power plants should account for these restrictions.
- There is little representative minute-to-minute wind data presently available for assessing dynamic impacts of large clusters of wind turbines.
- An important potential dynamic constraint to WT penetration is minute-to-minute ramping requirements imposed on the rest of the system generation on a daily basis. This applies to both isolated and some interconnected utility systems.
- System frequency excursion limitations are an important dynamic consideration for isolated utility systems.
- Dynamic impacts of wind turbine clusters will be site specific.
- Consideration of wind power plant output fluctuations under utility light loading conditions, as well as peak loads, is important.
- The conclusions of this study are considered as preliminary, due to the present lack of suitable site specific wind data and field experience with large clusters of wind turbines.

Specific conclusions and observations with respect to large penetration of wind turbines on the HECO system are:

- The HECO system is stable with 80 MW of WT installed at Kahuku.

- Allowable HECO generation minute-to-minute ramping limits and frequency excursion limitations on a daily basis may require WT operating restrictions and/or increased spinning reserve.

RECOMMENDATIONS

The above conclusions indicate that utility system/wind power plant dynamic assessments are important in order to determine WT penetration limits and/or WT/utility system operating constraints. It is recommended that additional, more detailed utility system/wind power plant dynamic assessments be performed and that additional representative minute-to-minute wind fluctuation data and wind turbine and aggregate plant performance data be gathered.

Additional parametric minute-to-minute ramping assessments similar to those in this study should be performed using interconnected utility criteria. These calculations should consider systems with large units, different mix, such as coal vs. oil, different spinning reserve criteria, and alternative minute-to-minute ramping criteria. The resulting impacts should be assessed for a range of coincident wind power plant output.

Additional study is required to determine representative minute-to-minute wind fluctuation data and a corresponding coincident wind power plant output fluctuation model. The plant model should include the effects of wind variation across the rotor, individual unit performance characteristics, and multiple WT output coincidence factors.

Further development and refinement of appropriate wind turbine dynamic models for integrated WT/utility system stability analysis are recommended. These models should be compatible with existing utility stability programs, if possible. It is suggested that future example stability assessments be performed on utility systems which are less generation/transmission/load dense than the HECO system.

It is also recommended that additional study be performed to determine the potential consequences of increasing allowable rate and frequency of ramping on utility generating units. The study should consider both large and small generating units which are subject to cycling, including both coal and oil fired units with once-through and drum-type boilers. The results of such a study would be of benefit for future assessment of potential dynamic impacts of wind power plants, as well as other intermittent energy sources.

Section 7

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Appendix A

HECO SYSTEM DATA

Appendix A presents HECO system data. Table A-1 describes the projected 1985 HECO generation system by power plant, including unit number and rating. Table A-2 provides the 138 kV HECO transmission line lengths, for lines shown in Figure 2-1. Table A-3 presents a breakdown of 1985 projected peak loads, and Table A-4 presents a breakdown of 1985 projected minimum loads. Impedance data for the 138 kV transmission system shown in Figure 2-1 is presented in Table A-5. Figures A-1 and A-2 present detailed impedance data for the Kahe and Waiau power plants. Figure A-3 presents the simplified representation used for the Honolulu area, including approximate simplified impedance representation of the 46 kV and 11 kV Honolulu distribution system. Figure A-4 presents impedance data for wind turbines installed at Kahuku and connected to the HECO system at Wahiawa. Impedance data for 80 MW connected via a 138 kV transmission line and 22 MW connected via the existing 46 kV system are presented. These data are supplemented by HECO machine data assumptions described in Appendix C.

Table A-1

PROJECTED 1985 HECO GENERATION SYSTEM

KAHE Unit	KAHE MW Rating	WAIAU Unit	WAIAU MW Rating	HONOLULU Unit	HONOLULU MW Rating
K 1	88	W 1	8	H 5	23
K 2	88	W 2	18	H 7	42
K 3	90	W 3	52	H 8	55
K 4	90	W 4	52	H 9	60
K 5	141	W 5	60	TOTAL	180
K 6	141	W 6	57		
TOTAL	638	W 7	90		
		W 8	90		
		W 9	52		
		W 10	52		
		TOTAL	531		

Table A-2

HECO 138 kV TRANSMISSION LINE LENGTHS

LINE DESCRIPTION				APPROXIMATE LENGTH IN MILES	(km)
Waiau	to	Koolau	Ckt. No. 1	13.2	(21.2)
Waiau	to	Koolau	Ckt. No. 2	13.3	(21.4)
Waiau	to	Kahe		18.9	(30.4)
Waiau	to	Wahiawa		12.1	(19.5)
Kahe	to	Wahiawa		17.8	(28.6)
Koolau	to	Pukele		6.4	(10.3)
Halawa	to	Kahe	Ckt. No. 1	21.0	(33.8)
Halawa	to	Kahe	Ckt. No. 2	20.4	(32.8)
Halawa	to	School		5.0	(8.0)
Iwilei	to	Halawa		6.2	(10.0)
School	to	Iwilei		0.6	(1.0)
Halawa	to	Koolau		9.8	(15.8)
Halawa	to	Makalapa		4.2	(6.8)
Waiau	to	Makalapa		4.2	(6.8)
Koolau	to	Kamoku		4.3	(6.9)
Halawa	to	Pukele		10.0	(16.1)
Halawa	to	Kamoku		13.8	(22.2)

Table A-3

1985 PROJECTED HECO SYSTEM PEAK LOADS

	MW	MVAR
Kahe	46.49	15.77
Halawa	59.07	27.80
Koolau	182.90	9.14
Pukele	186.12	37.96
Wahiawa	107.92	41.65
Waiau	110.75	41.63
Honolulu Area	195.39	75.42
Makalapa	81.79	48.33
Kamoku	60.39	12.32
Ceip	62.01	22.17
TOTAL SYSTEM NATIVE LOAD	1,136.00	353.10

Table A-4

1985 PROJECTED HECO SYSTEM MINIMUM LOADS

	MW	MVAR
Kahe	26.34	9.03
Halawa	28.91	11.79
Koolau	58.86	13.13
Pukele	83.40	3.73
Wahiawa	34.06	8.50
Waiau	38.89	23.18
Honolulu Area	64.02	14.63
Makalapa	52.66	36.35
Kamoku	27.07	1.21
Ceip	26.69	12.53
Losses	36.10	17.48
TOTAL SYSTEM MINIMUM LOAD	477.00	151.56

Table A-5

HECO 138 kV TRANSMISSION SYSTEM IMPEDANCE DATA
(100 MVA BASE)

LINE DESCRIPTION				POSITIVE SEQUENCE IMPEDANCE (%) R	X
Waiau	to	Koolau	Ckt. No. 1	.6496	4.0073
Waiau	to	Koolau	Ckt. No. 2	.6495	4.0347
Waiau	to	Kahe		.9423	5.416
Waiau	to	Wahiawa		.613	5.416
Kahe	to	Wahiawa		.878	5.05
Koolau	to	Pukele		.302	1.83
Halawa	to	Kahe	Ckt. No. 1	.997	5.938
Halawa	to	Kahe	Ckt. No. 2	1.0247	6.084
Halawa	to	School		.22	1.64
Iwilei	to	Halawa		.265	1.994
School	to	Iwilei		.018	.21
Halawa	to	Kookau		.476	3.028
Halawa	to	Makalapa		.183	1.345
Waiau	to	Makalapa		.155	1.473
Koolau	to	Kamoku		.631	3.705
Halawa	to	Pukele		.49	2.89
Halawa	to	Kamoku		.677	3.98

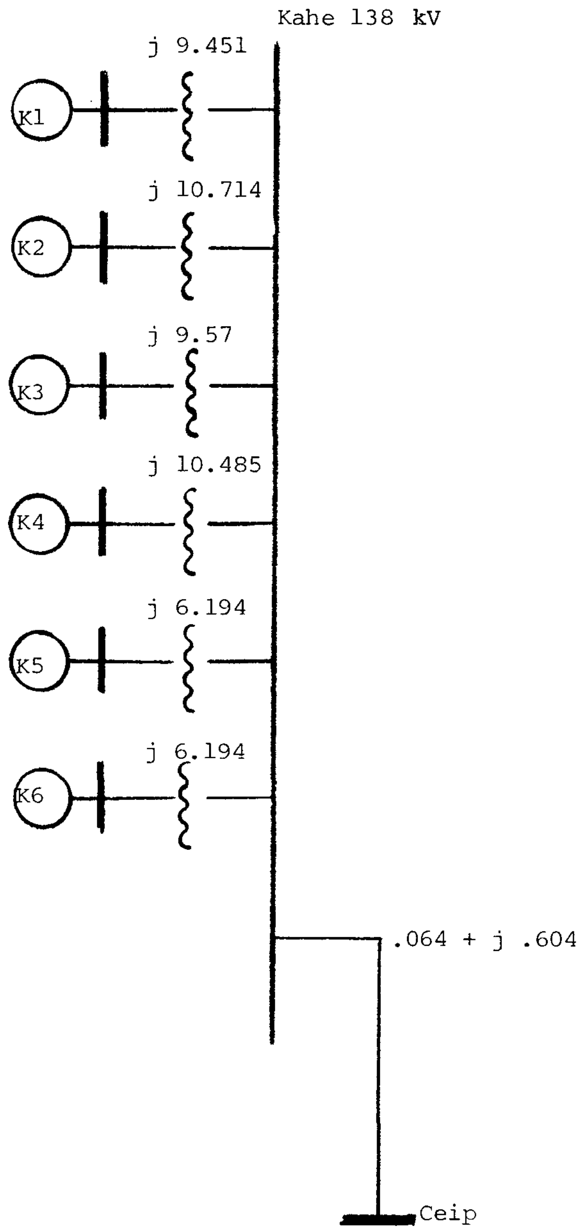


Figure A-1. Kahe Power Plant Impedance Diagram
(% on 100 MVA Base)

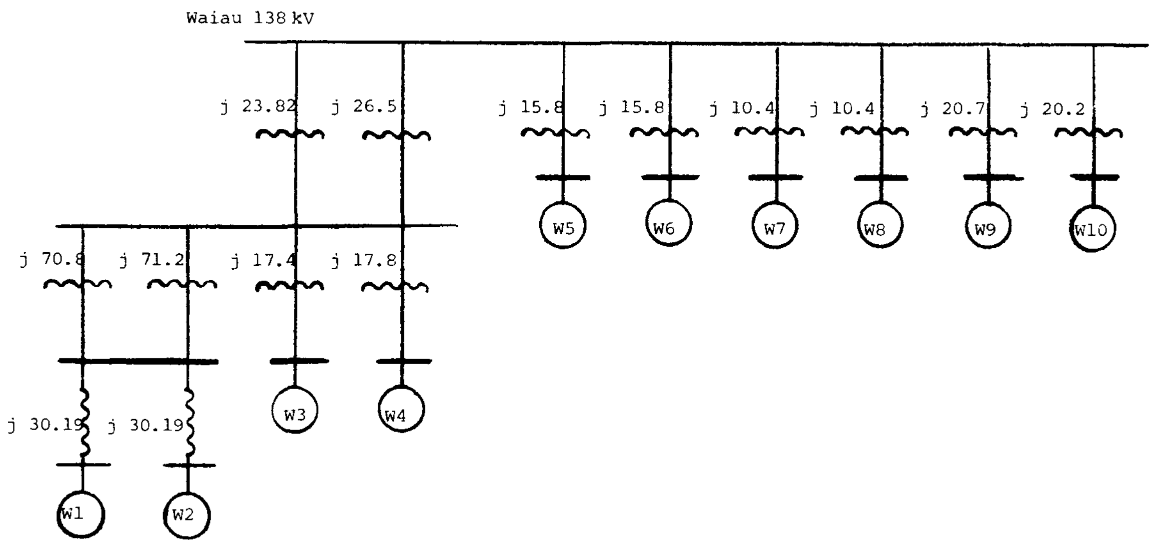


Figure A-2. Waiau Power Plant Impedance Diagram (% on 100 MVA Base)

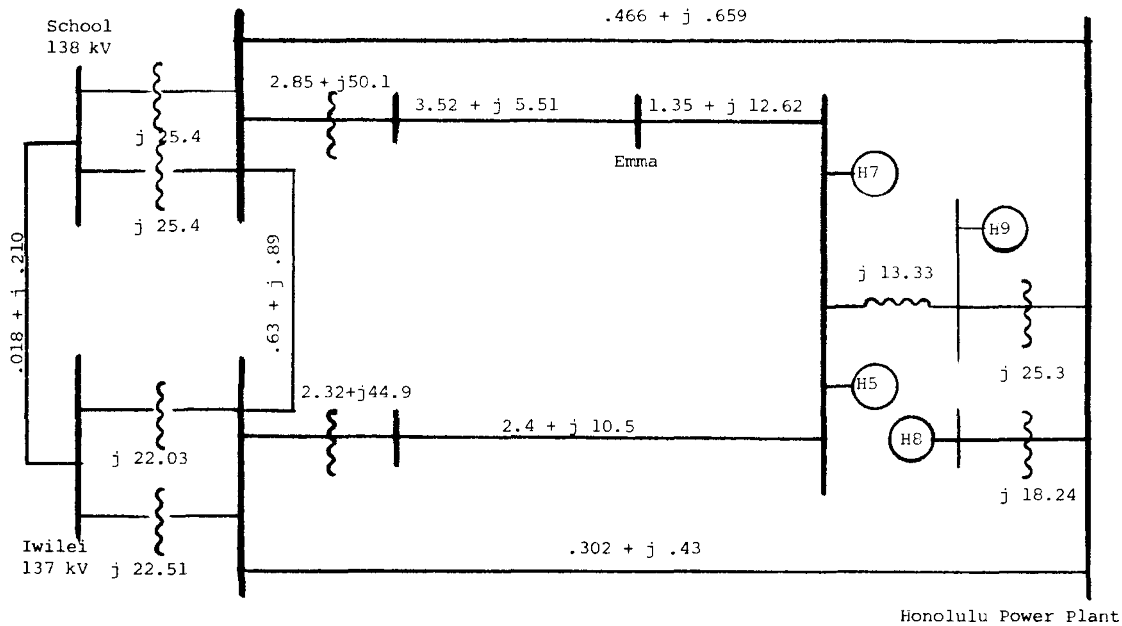
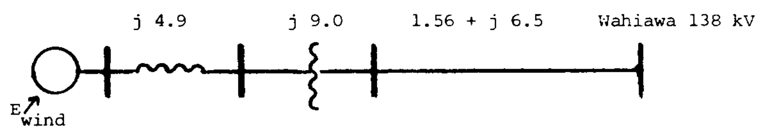


Figure A-3. Honolulu Area Representation (% on 100 MVA Base)

80 MW Wind Power Plant Connected via 138 kV Transmission Line



22 MW Wind Power Plant Connected via 46 kV Transmission System

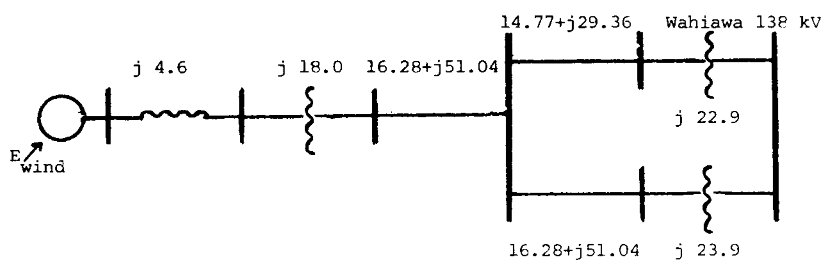


Figure A-4. 80 and 22 MW Wind Power Plant Impedance Data (% on 100 MVA Base)

Appendix B

STEAM TURBINE GOVERNING CHARACTERISTIC

The nominal steam turbine governor response is invariant with respect to initial turbine load. However, this model of governor response cannot hold if a turbine already at 100% output is called on by its governor for more power. One reference, (4), describes this effect graphically - - see Figure B-1. The nominal characteristic is linear, that is the "droop" or β_1 is constant for all initial turbine power loads and frequency deviations. The figure also shows the actual characteristic for four initial turbine loads. Using Figure B-1, β_1 as a function of initial load for both minus 0.1 and minus 0.4 Hz frequency deviations was obtained and plotted in Figure B-2. It can be seen that the value of β_1' becomes less than half that of the nominal (based on 5% droop) at high initial loads.

The calculations for frequency excursions in Section 3 used curves fitted to the piecewise linear representations in Figure B-2:

- For Frequency Change = -0.1 Hz $\beta_1' = 1.7787\ L^{-1.5404}$
- For Frequency Change = -0.4 Hz $\beta_1' = 1.6003\ L^{-1.6763}$

Where L = Fraction of Rated Turbine Load

The relationships are considered useful for an initial assessment only. Further verification and modeling are indicated for anything other than preliminary results. One problem in particular is extrapolation of the curves to power levels below 60 percent, as was done in the present study to maintain consistency in the absence of further data. It is felt that the high values obtained (e.g., $\beta_1' = 7.3$ at L = 30 percent) tend to indicate exaggerated benefits for increasing spinning reserve levels. Again, it is emphasized that these calculations are an initial assessment.

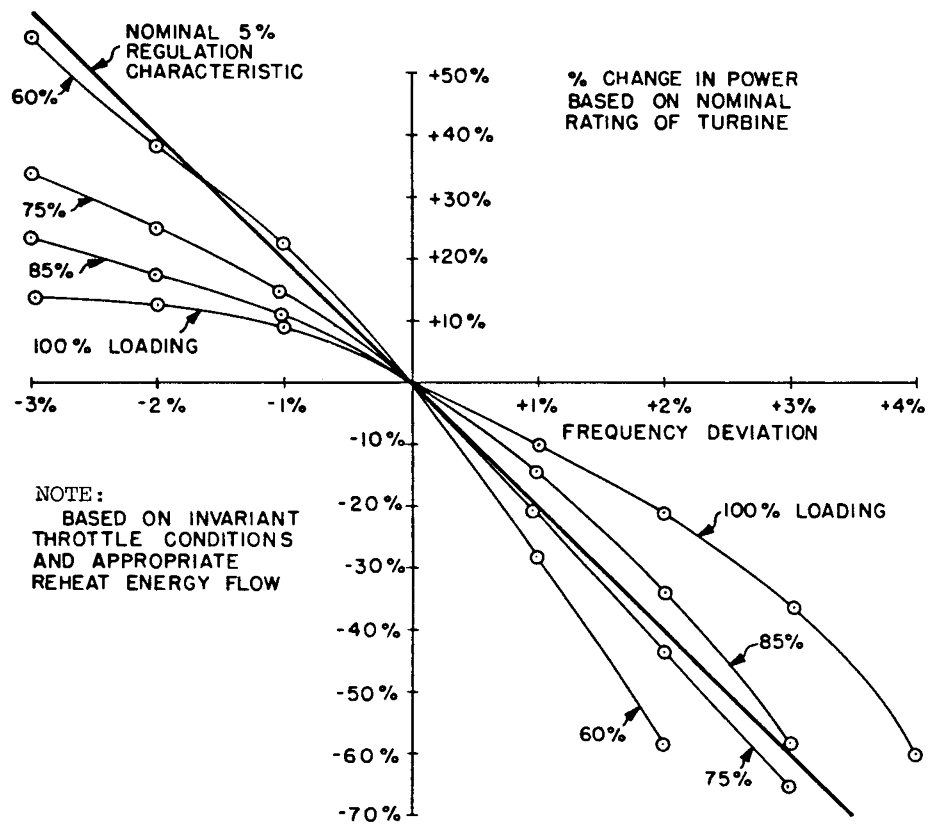


Figure B-1. Steady-State Fossil Fuel Steam Turbine Regulation Characteristics

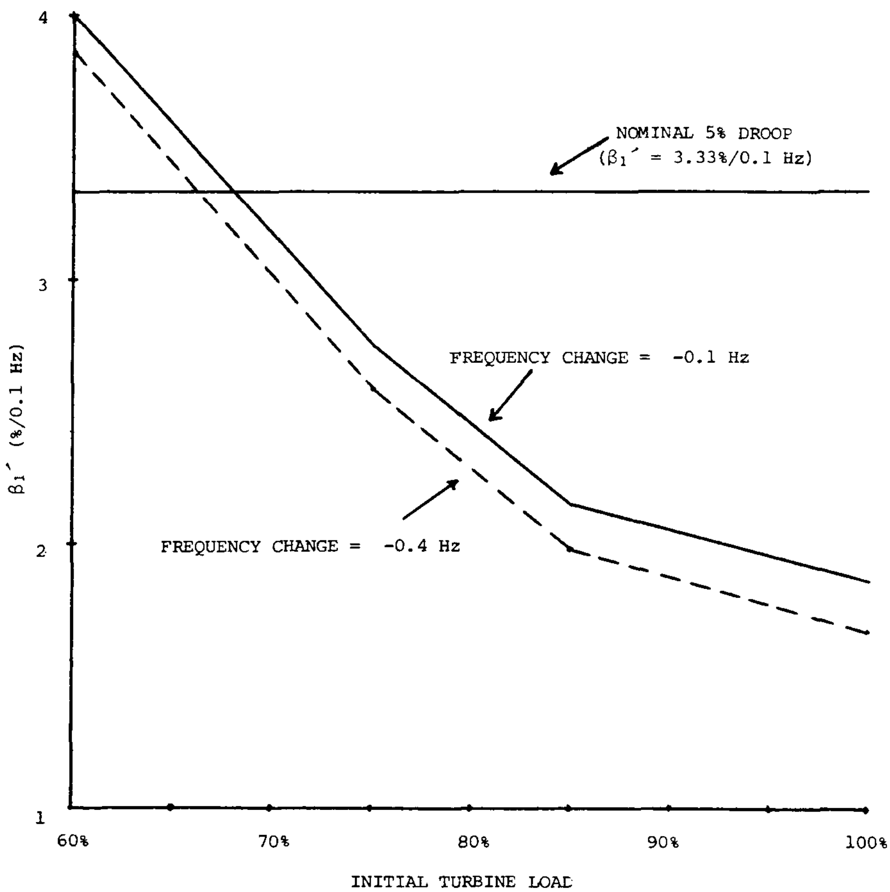


Figure B-2. Steam Turbine Governing Characteristic

Appendix C

HECO MACHINE DATA

MACHINE DATA

HECO machine data used for the stability analysis was based on HECO supplied generator and turbine data included in Table C-1.

EXCITER DATA

For all the units with an exciter (other than a manual exciter), the IEEE Type 1 exciter model was used, as shown in Figure C-1. Two sets of exciter system parameters are listed below. The units with manual exciters are H5, H7, W1, and W2.

	K_A	T_A	$V_A max$	$V_A min$	K_E	T_E
W	400	0.05	3.5	-3.5	-0.17	0.95
GE	25	0.2	1.0	-1.0	-0.05	0.561

	T_{SE}	A_{EX}	B_{EX}	μ_s	K_G	T_R
W	1.0	0.0039	1.555	0.04	1.0	0.0
GE	0.35	0.00165	1.648	0.257	1.0	0.0

Legend:

W Westinghouse

GE General Electric

For a definition of these symbols, refer to the IEEE Committee Report (14) and the Philadelphia Electric Stability Program User's Guide (15).

TURBINE/GOVERNOR SYSTEM

The turbine/governor system representation is presented in Figure C-2. These symbols are also defined in (15).

Table C-1

HECO MACHINE DATA

UNIT	GENERATOR WR^2 lb.-ft.^{2}	($N-m^2$)	TURBINE WR^2 lb.-ft.^{2}	($N-m^2$)	x'_d 100 MVA BASE %	MANUFACTURER
Honolulu						
H5	70,100	(29,200)	178,200	(74,200)	56.0	W
H7	37,400	(15,600)	42,130	(17,500)	22.5	W
H8	41,600	(17,300)	42,830	(17,800)	19.7	W
H9	41,600	(17,300)	42,785	(17,800)	19.5	W
Waiau						
W1	7,850	(3,260)	9,870	(4,110)	87.5	W
W2	16,100	(6,700)	25,840	(10,800)	51.7	W
W3	44,500	(18,500)	42,130	(17,500)	20.2	W
W4	44,500	(18,500)	42,130	(17,500)	20.2	W
W5	41,600	(17,300)	45,451	(18,900)	19.5	W
W6	40,139	(16,700)	45,452	(18,900)	19.5	W
W7	65,625	(27,300)	76,698	(31,900)	10.5	W
W8	65,625	(27,300)	76,698	(31,900)	10.5	W
W9	149,261	(62,100)	--	(--)	18.4	GE
W10	149,261	(62,100)	--	(--)	18.4	GE
Kahe						
K1	65,620	(27,300)	76,700	(31,900)	10.5	W
K2	65,620	(27,300)	76,700	(31,900)	10.5	W
K3	57,791	(24,100)	61,468	(25,600)	13.4	GE
K4	57,791	(24,100)	61,468	(25,600)	13.4	GE
K5	92,806	(38,600)	137,285	(57,100)	6.9	W
K6	92,806	(38,600)	137,285	(57,100)	6.9	W

Legend:

W Westinghouse

GE General Electric

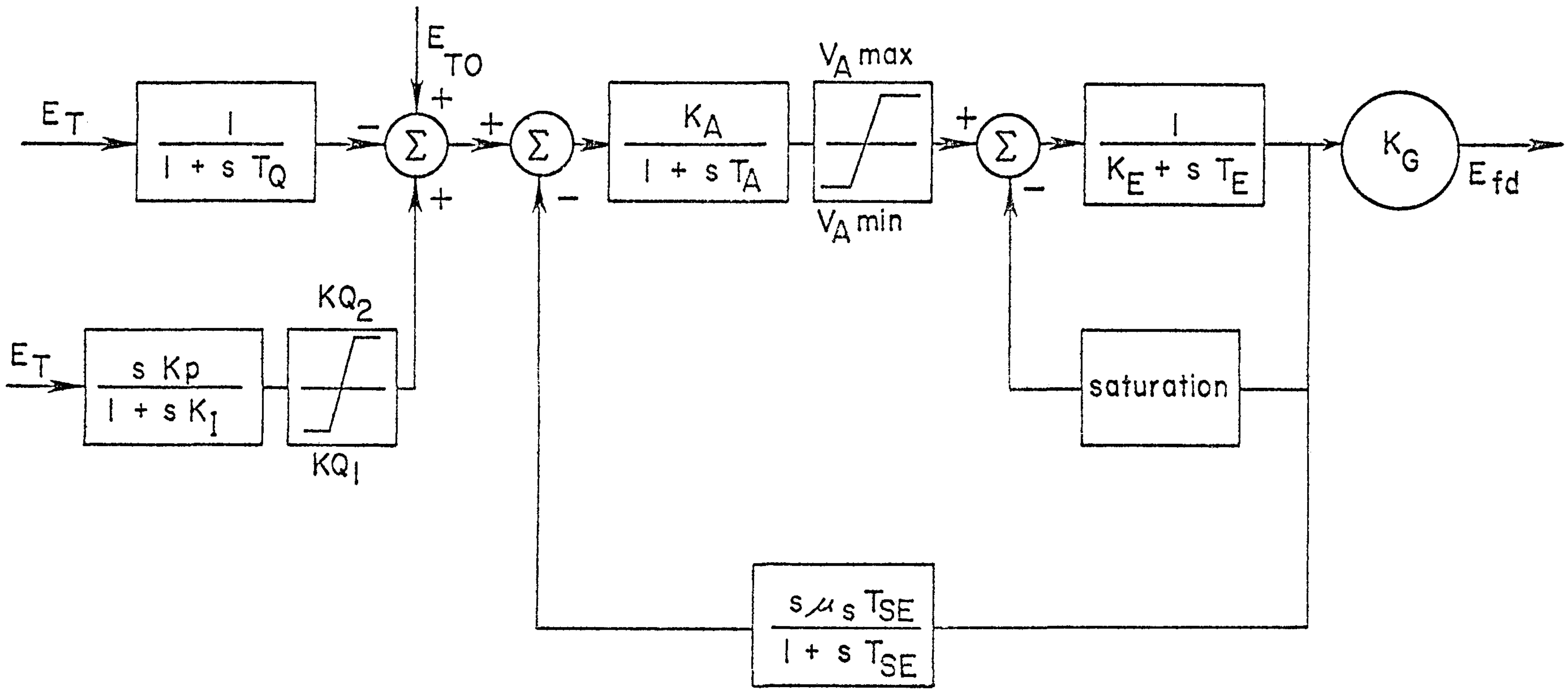


Figure C-1. IEEE Type 1 Exciter System

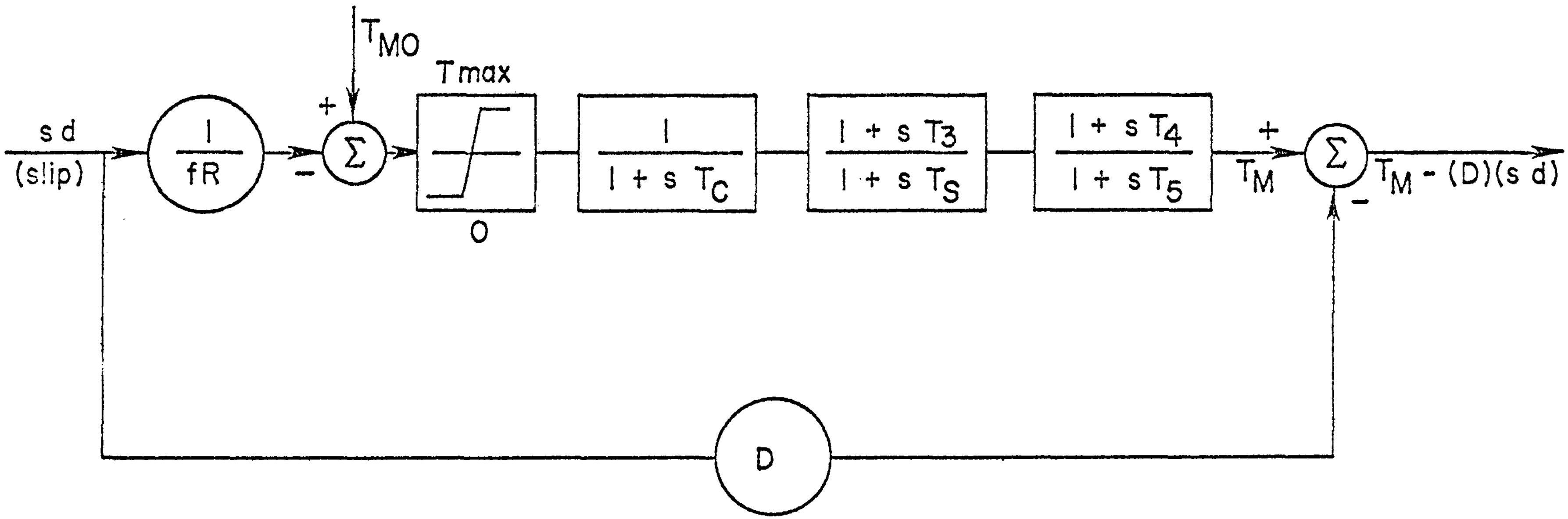


Figure C-2. Turbine And Governor System

Appendix D

WT DYNAMIC MODEL

The purpose of the short-term stability calculations in this study was to determine the relative stability of the HECO system with and without a large WT cluster installed. For this initial assessment, the WT cluster was represented as a single combined source with intermachine oscillations among the individual WT units neglected. The WT cluster dynamic model was based on MOD-2 data developed in NASA studies, and was received through informal correspondence from T.W. Reddoch.

The WT cluster was represented using a two-mass model shown in Figure D-1. The model consists of one synchronous machine at bus G representing the WT cluster generators, and another synchronous machine at bus T representing the WT cluster turbines. The machine at bus G contains the rotor inertia and transient reactance of the generators. The excitation system used for controlling the voltage at bus G was an IEEE Type 1 system (described in Appendix C). E_F is the exciter output voltage.

The machine at bus T contains the inertia of the WT cluster turbines. Wind torque, T_W, is applied to this synchronous machine. The voltage is not controlled at bus T, and E_F is a constant.

The shaft stiffness between the turbine and generator, K_{HT}, is represented in the two-mass model as a transmission line of reactance X' between bus T and G and a transient reactance X'_T assumed for the synchronous machine at bus T. The relationship between shaft stiffness constant, K_{HT}, and the electrical reactances X' and X'_T is as follows, where δ_G is the electrical angle of the machine at bus G and δ_T is the electrical angle of the machine at bus T.

$$X' + X'_T = \frac{1}{K_{HT}} \cos(\delta_G - \delta_T) \qquad \text{(D-1)}$$

The wind turbine analog model corresponding to the two-mass WT cluster is shown in Figure D-2. The nomenclature used in the analog model is as follows:

- D is the machine shaft damping factor
- D_{12} is the quill shaft damping factor
- δ_G is the electrical angle of the machine at bus G
- δ_T is the electrical angle of the machine at bus T
- K_{HT} is the turbine-generator shaft stiffness constant
- T_{max} is the maximum torque output
- T_{min} is the minimum torque output
- T_m is the mechanical torque
- T_{mo} is the initial mechanical torque
- I_T is the turbine rotor inertia

The parameter values used for WT cluster analog model are as follows:

- I_T = 10 seconds on a 100 MVA base
- K_{HT} = 0.1 per unit torque per radian
- D_{12} = 0.1/60 per unit torque per cycle
- D = 1.0/60 per unit torque per cycle
- T_{max} = 84 MW for 80 MW WT cluster
- T_{min} = 0 MW

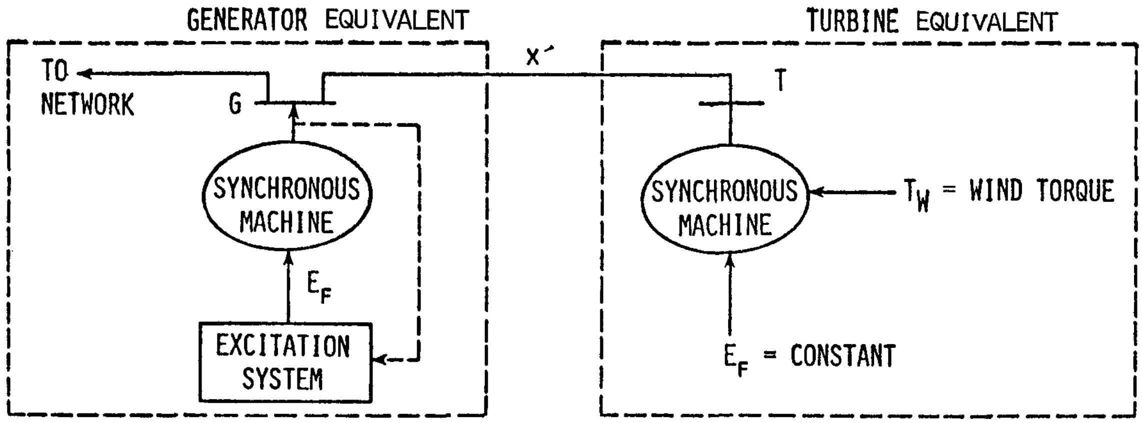


Figure D-1. Computer Representation Of WT Cluster

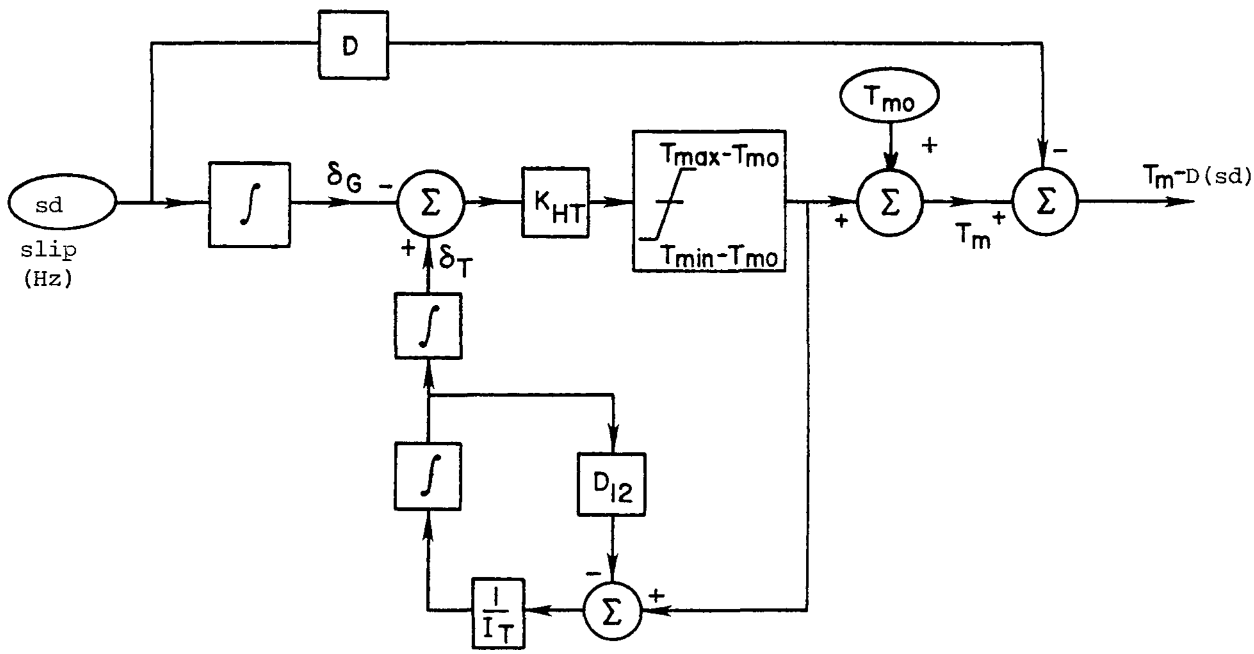


Figure D-2. Wind Turbine Analog Model

Appendix E

REPRESENTATIVE KAHUKU WIND FLUCTUATION DATA

Figure E-1 contains a representative sample of Kahuku wind fluctuation data taken at one second intervals on October 10, 1978, as well as the corresponding integrated 10, 30, and 60 second wind fluctuation data. The average wind speed was 14.57 mph (6.5 m/s) during the period of measurement.

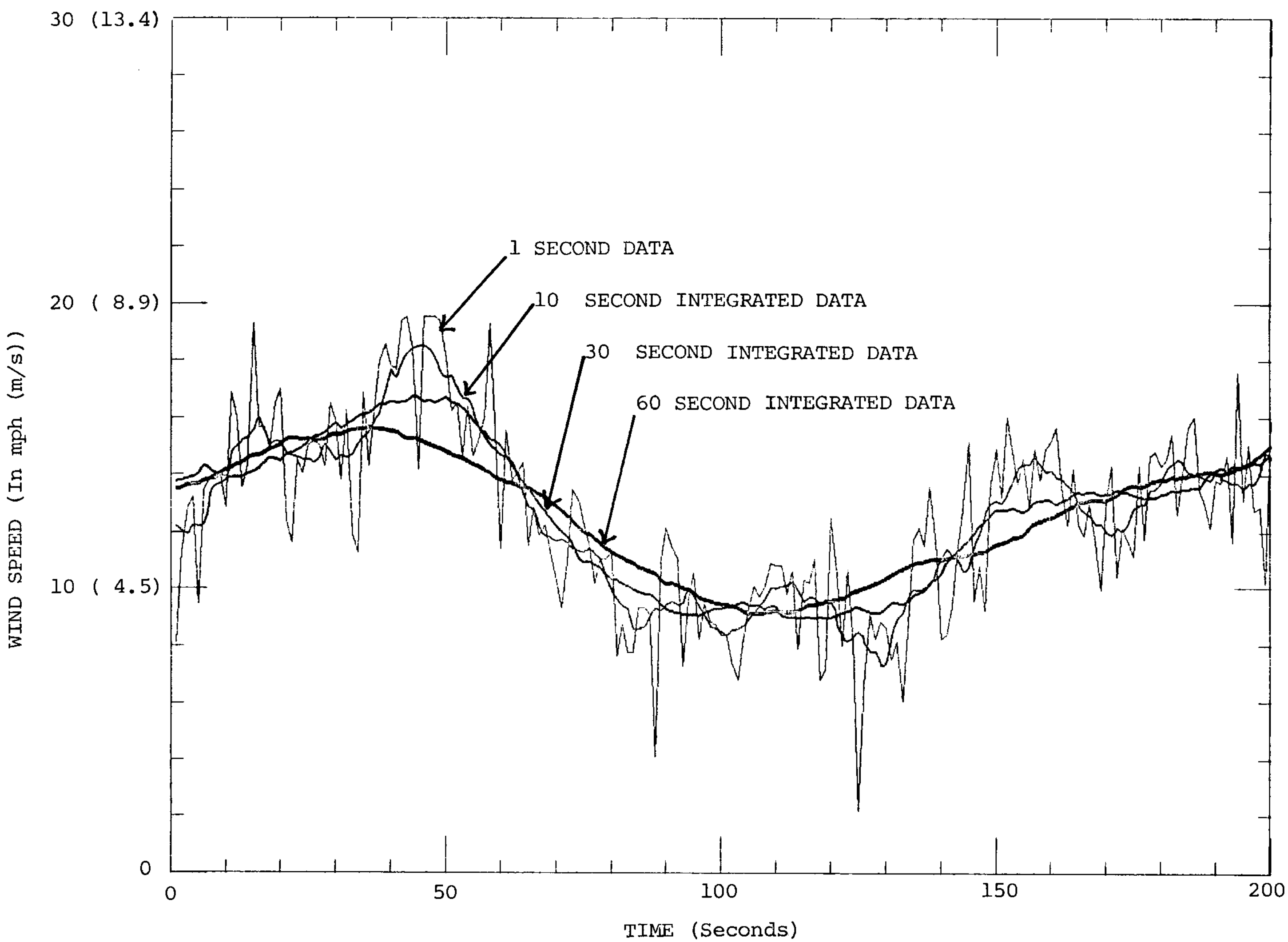


Figure E-1. Representative Sample Of Kahuku Wind Fluctuation Data

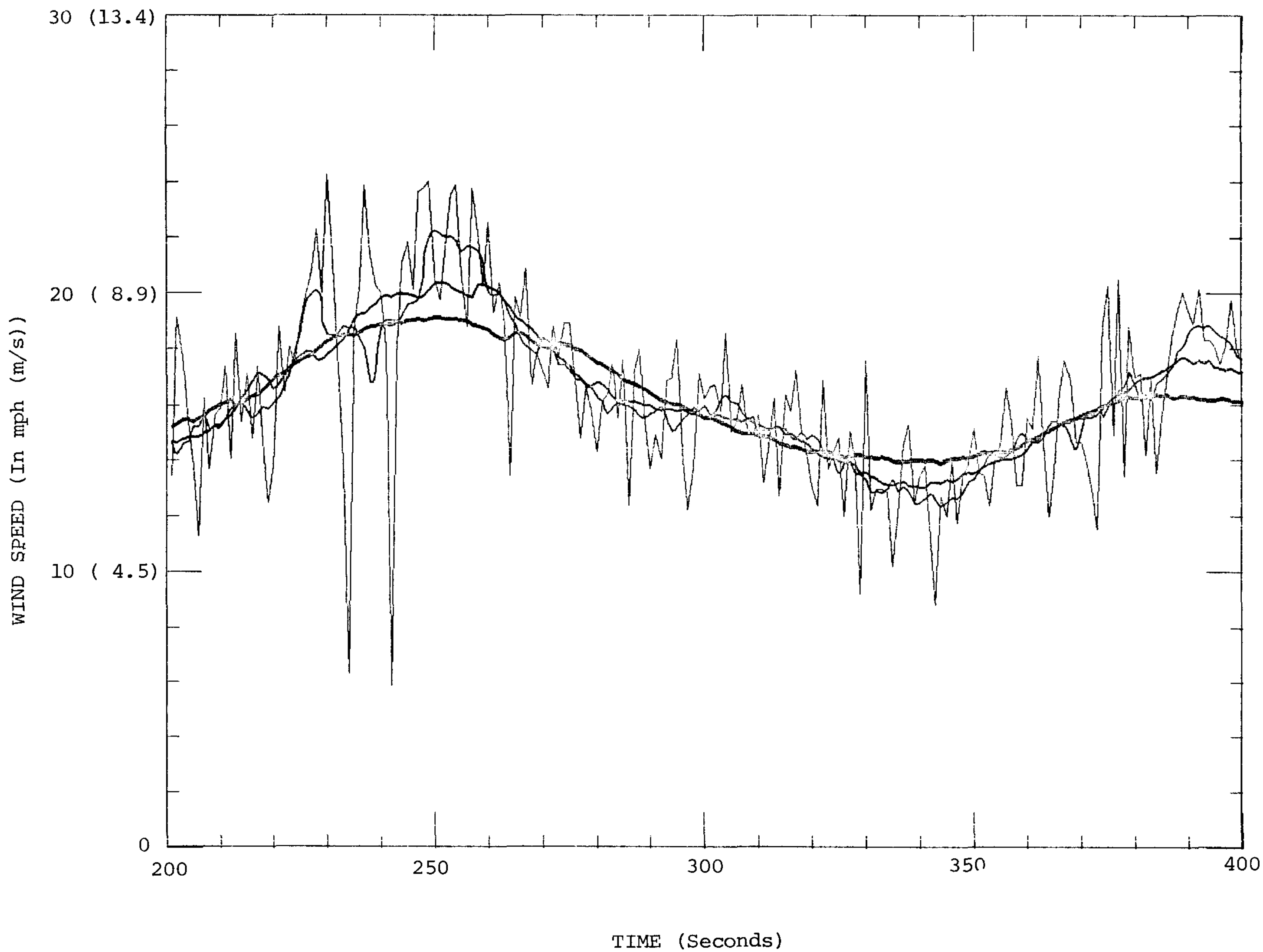


Figure E-1. Representative Sample Of Kahuku Wind Fluctuation Data (Continued)

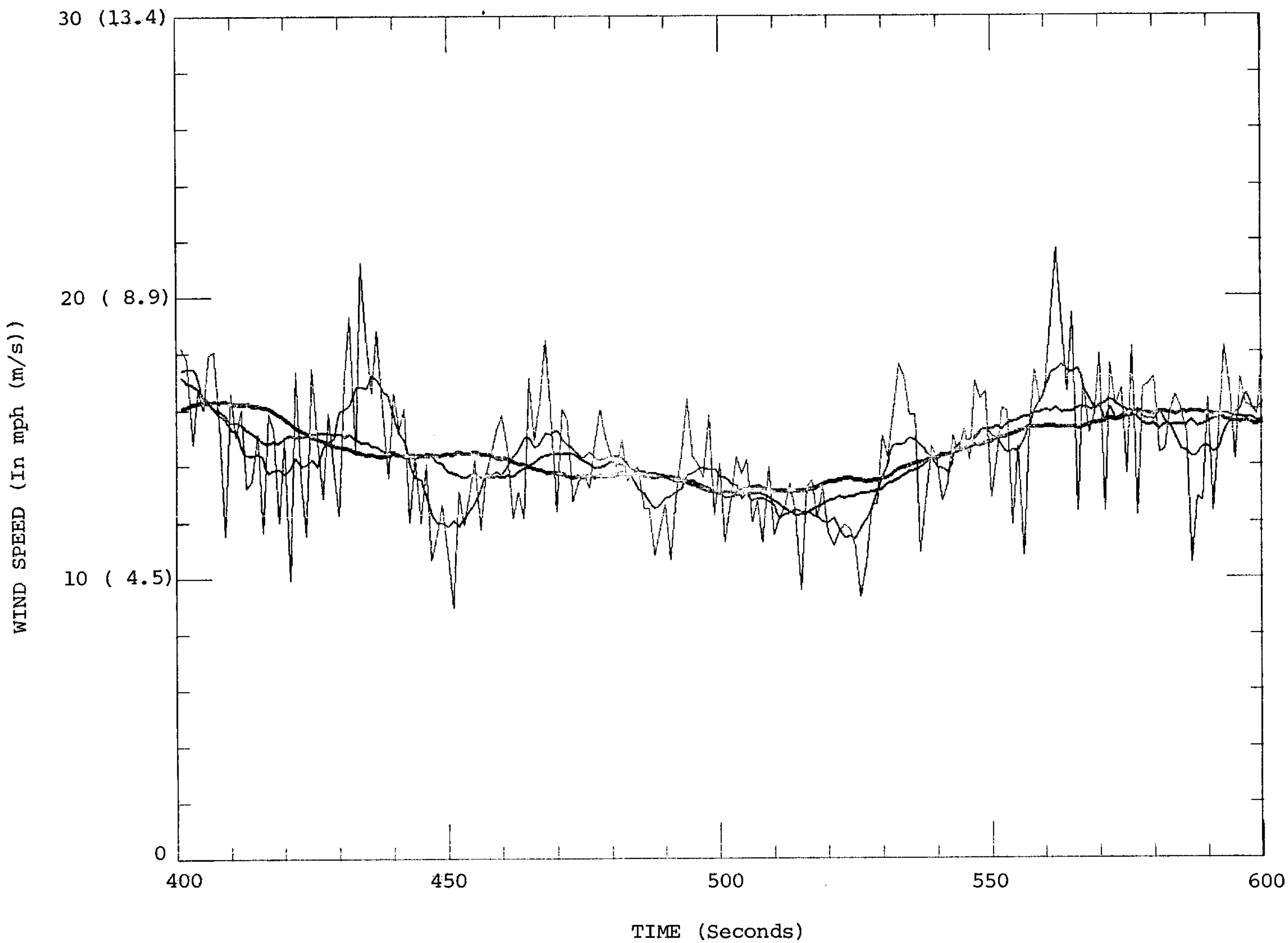


Figure E-1. Representative Sample Of Kahuku Wind Fluctuation Data (Continued)

Appendix F

REPRESENTATIVE SHORT-TERM STABILITY SWING CURVES

This appendix contains representative swing curves resulting from the short-term transient stability analysis performed in this study. All of these curves are for the "80 MW wind case" described in Section 5. The bus and generator designations are consistent with the HECO system description in Section 2 and Appendix A. Three new bus designations are introduced in this appendix: 11KV3, WIND2, and WIND3. The 11KV3 bus is an actual 11 kV bus in the Honolulu area. WIND2 is the bus for the synchronous machine representing the generators in the WT cluster model, and WIND3 is the bus for the synchronous machine representing the turbines in the WT cluster model. The WT cluster model is described in Appendix D.

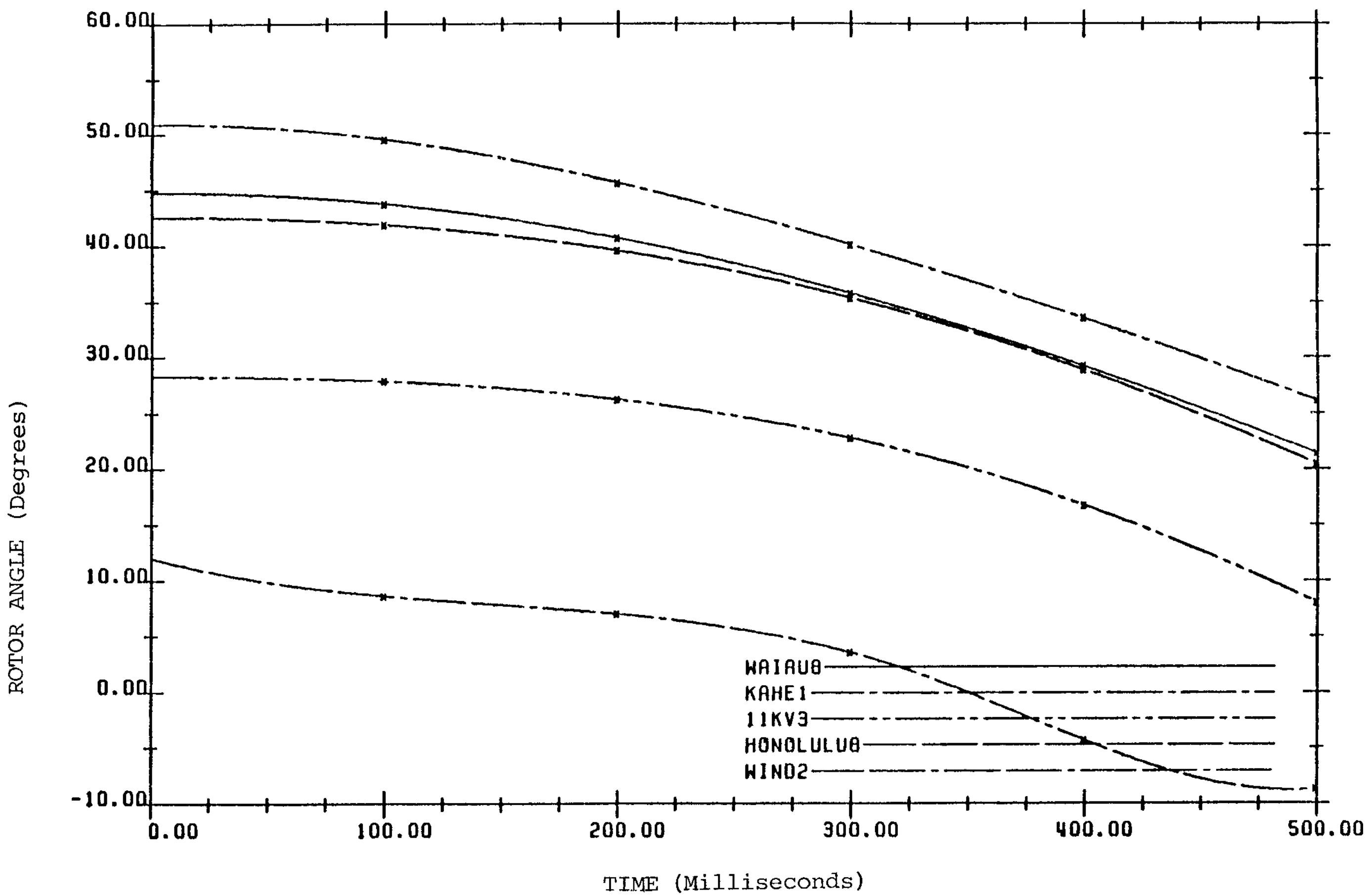


Figure F-1. Generation Swing Curves For Tripping Kahe 6 At Peak Load - First Half Second

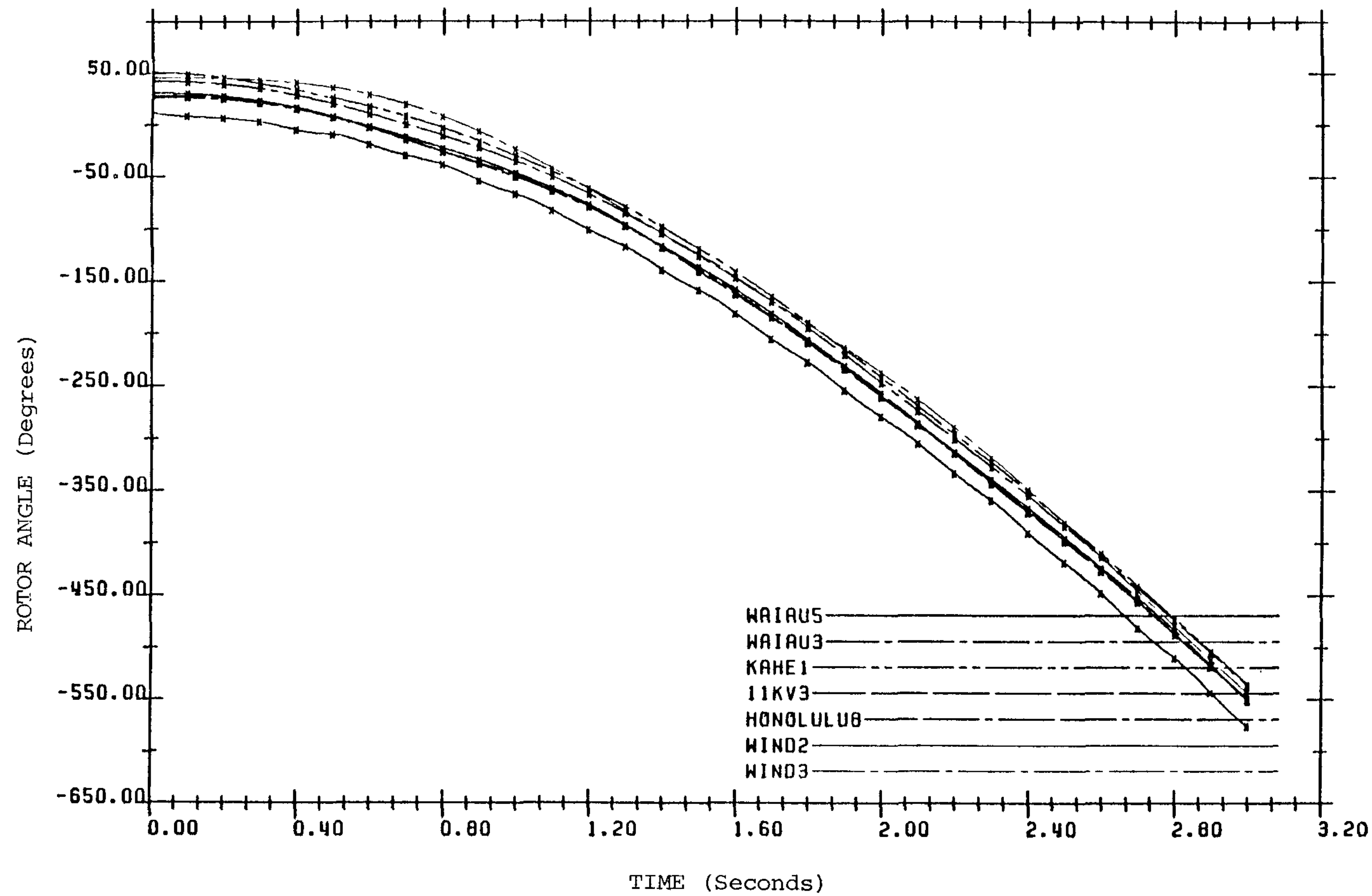


Figure F-2. Generation Swing Curves For Tripping Kahe 6 At Peak Load - Full Three Seconds

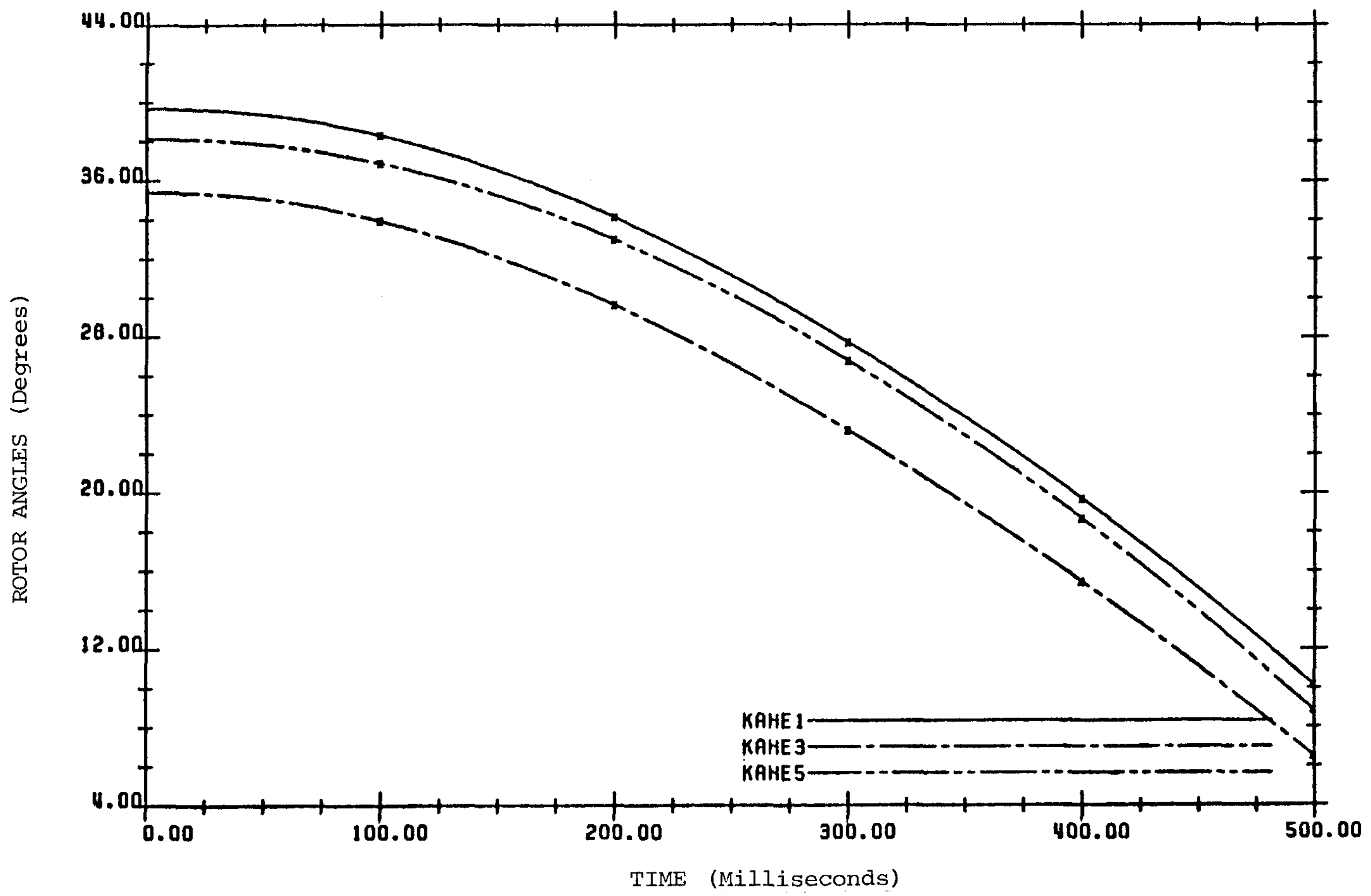


Figure F-3. Generation Swing Curves For Tripping Kahe 6 At Minimum Load - First Half Second

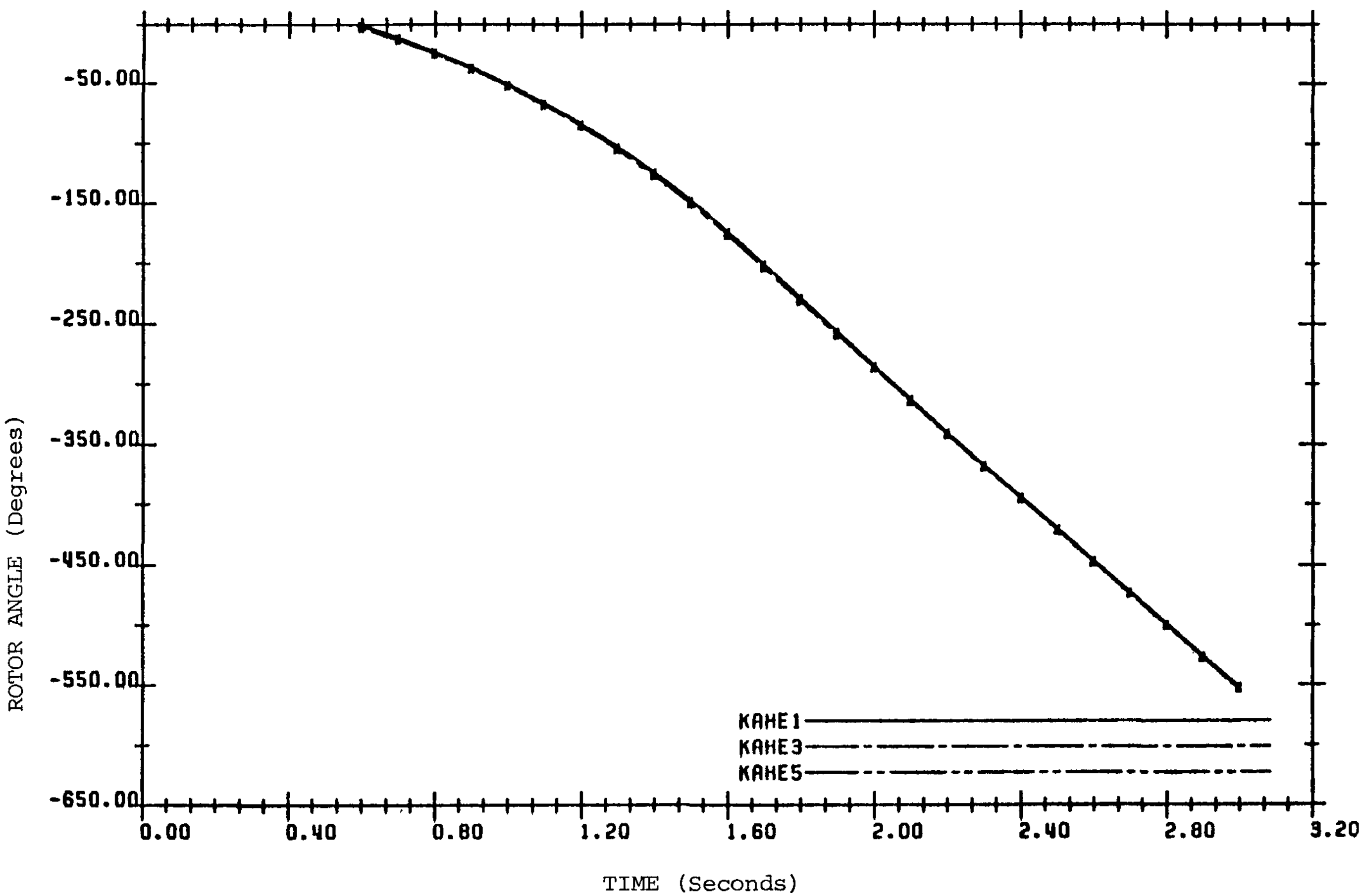


Figure F-4. Generation Swing Curves For Tripping Kahe 6 At Minimum Load - Full Three Seconds

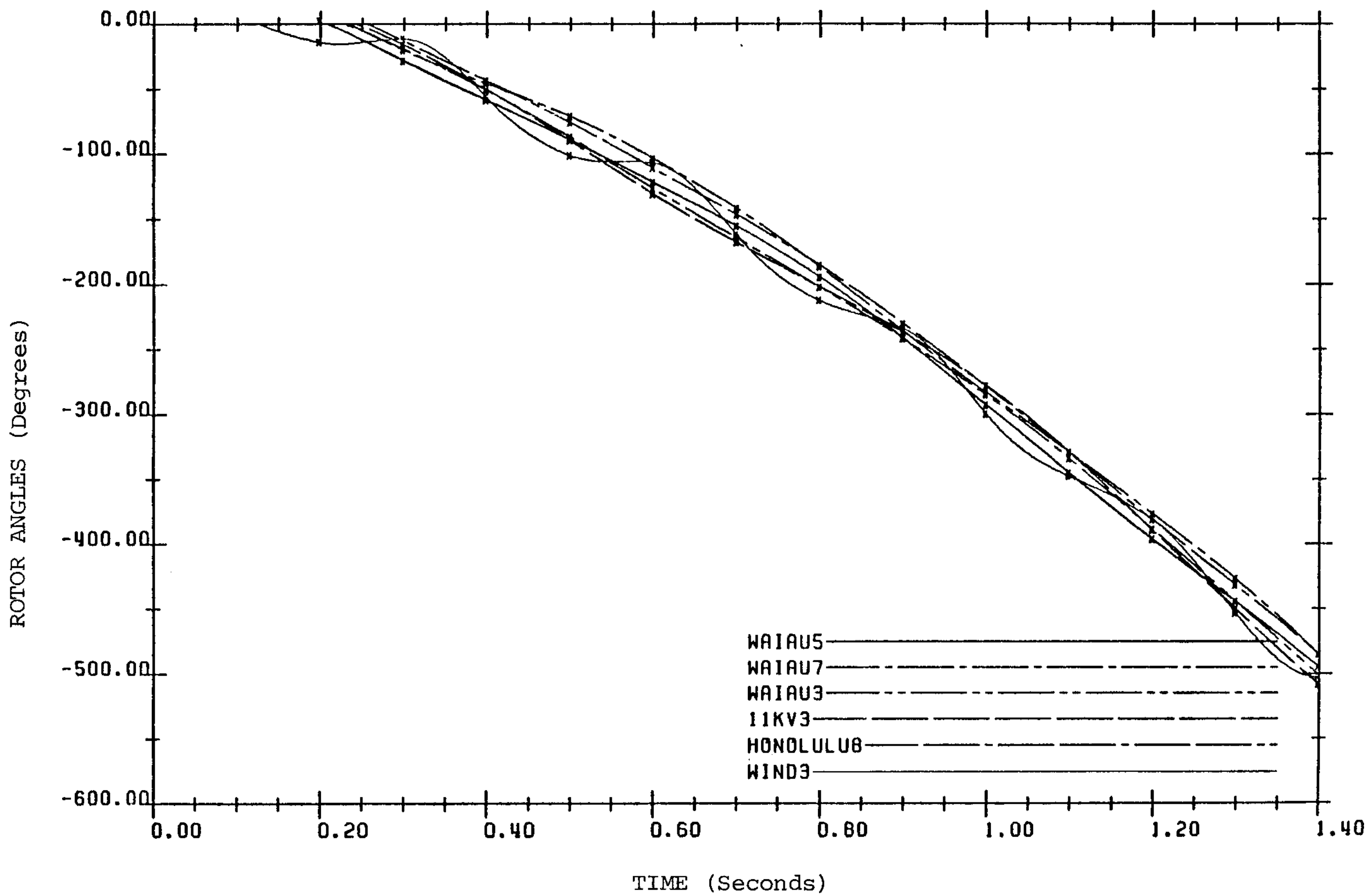


Figure F-5. Generation Swing Curves For Separation Of Kahe Power Plant And Ceip At Peak Load - First 1.4 Seconds