August 31, 1981

Docket No. 50-244
LS05-81-08-086

Mr. John E. Maier, Vice President
Electric and Steam Production
Rochester Gas and Electric Corporation
89 East Avenue
Rochester, New York 14649

RECEIVED
SEP 02 1981
U.S. NUCLEAR REGULATORY COMMISSION

Dear Mr. Maier:

SUBJECT: REFERENCES FOR SEP TOPICS VI-7.F, VII-3, VII-6 AND VIII-2
R. E. GINNA

Your letter of August 10, 1981 requested clarification of the references used in our recently published safety evaluation reports (SER) on the subject topics. In each case a contractor technical report (TER) had been published earlier.

The appropriate references are:

Topic	TER	Forwarded
VI-7.F	1328F	March 24, 1981*
VII-3	0341J	April 2, 1981**
VIII-2	0044J	April 2, 1981

* ID number deleted as a result of clerical error
** Last two digits of ID number were reversed in SER

As requested, we have enclosed the appropriate pages from NUREG/CR-1464.

Sincerely,

Dennis M. Crutchfield, Chief
Operating Reactors Branch No. 5
Division of Licensing

Add: Gary Staley
Alan Wang

Enclosure:
As stated

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cc w/enclosure:
See next page

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Enclosure 22

4. SOME ASPECTS OF POWER SYSTEM FREQUENCY DECAY RATES AND PWR REACTOR COOLANT PUMPS

4.1 Statement of the Problem of Power Grid Frequency Decay

It is assumed that as a result of an underfrequency signal a PWR is tripped off line. Since an underfrequency trip signal indicates an inadequate electric supply from the primary source, the emergency system with emergency coolant pumping is called on line. During the changeover period, which is of the order of a few seconds, it is assumed that the reactor coolant pumps will continue to pump coolant to ensure that the departure from nucleate boiling ratio (DNBR) limits will not be exceeded. Reactor coolant pumps are designed, and provided with sufficiently massive flywheels, to ensure that even with power to them interrupted, their momentum will be sufficient to provide adequate cooling flow during their coast-down period as the emergency system pumps are brought up.

A concern has arisen that the power grid might not only cease supplying the reactor coolant pumps with power at such a time but under some circumstances could also withdraw the stored mechanical energy in the pump-motor system. During such an event the grid frequency would decay, and the pump motor would become a generator, supplying power to the grid, and the stored energy would be withdrawn from the pump-motor system. The rate of decay is the measure of the rate at which the stored energy would be withdrawn.

ORNL has been studying some aspects of frequency decay for the NRC. Initially, ORNL reviewed reports of studies by other companies of such pump motors and the problems that frequency decay could cause. At the direction of the NRC, ORNL limited its study to assessment of what is the maximum credible expected rate of frequency decay on a power system in the United States and to recommend what further questions must be raised to resolve these problems.

A more precise statement of what is meant by maximum credible frequency decay rate is as follows:

1. The concern over frequency decay previously mentioned is limited to frequency decay at a bus which supplies electric power to a nuclear power plant and which, while supplying that power, is connected electrically to other loads approximately equal to or greater than the nuclear power plant load.

2. Specification of a "maximum credible frequency decay rate" would not be meaningful if the rate is not sustained long enough to cause a significant drop in line frequency. In place of such a rate one should consider the maximum credible drop in line frequency that might occur during any subinterval of a specified critical time interval.

Exactly what critical time and maximum frequency drop should be specified depends on the design characteristics of the reactor system, including, importantly, the frequency level at which a reactor trip signal is generated.

The approach to the frequency decay problem and its possible effect on reactor coolant pumps has been to compute the frequency decay rate that a system could sustain without exceeding DNBR limits and then to show that such a rate is incredible on the United States power grid.

Three different PWR designs were examined, and the calculations indicate they could tolerate decay rates of 2.3, 3.0, and 6.8 Hz/s, respectively. (These calculations were made by three different organizations, and at this time, we have no way of knowing whether the different results were due to substantial design differences or to substantial differences in the computational approach.) It has been ORNL's task, principally, to determine whether these frequency decay rates are greater than the maximum credible decay rate of the power grid.

By way of anticipation, we have found that computations of grid behavior in some cases indicate the possibility of higher decay rates: there is at least one recorded case of a decay rate of 10.7 Hz/s. Under these circumstances, we must conclude that the maximum credible decay rate must be at least about 10 Hz/s, which does not support this logical approach to the problem.

We must emphasize, however, that simply because this approach to the problem does not appear to provide a fruitful resolution, it does not follow that frequency decay poses a very serious safety issue.

For this to be a problem it appears that simultaneously (1) there must be a steep frequency decay (the probability that this will occur is quite low), (2) the generator must be off the grid, and (3) all the reactor coolant pumps must remain connected to the grid. The probability that these three events would occur simultaneously is very small.

Sequences of events where the reactor shutdown precedes the generator trip or frequency decay by as little as 2 or 3 s appear to contain no potential for problems of the kind considered here. Moreover, even if the event did occur, the system may be able to accept its apparently limited consequences as a design basis event. The consequences may be further limited when one takes into explicit account the momentum contained in the coolant water itself and its relatively loose coupling back to the electric supply system.

Therefore, while we do not assert that our findings concerning frequency decay rates support assumptions made in previous approaches to this problem, we are of the opinion that it is much less than an urgent issue and can be put in a satisfactory context by an alternative approach.

4.2 Approach to An Estimate of Maximum Credible Frequency Decay Rate

To determine a reasonable estimate of maximum credible frequency decay rate, we have relied principally on three resources: discussions with experienced persons, review of computations, and study of the literature of recorded events.

In addition, we attempted some calculations of simple systems. It soon became clear, however, that to put sufficient realism into a computational model to make it competitive with calculations in the published literature would require more resources than were available.

The results of our survey approach are discussed in the paragraphs to follow.

4.2.1 Discussions with experienced persons: the statistical tail and the fallibility of experience

When a question concerns the average behavior of a system or the spread of conditions about the average, there are few better sources of information than those who have a long experience operating the system. If the question implies extremely unusual system behavior, and especially with negative connotations, replies from experienced operating persons are often of the nature of "impossible," "never heard of such a thing," "never in my experience," "ridiculous," "only an amateur would think of such a thing," etc.

Further complications can arise if the phenomenon under study is seldom monitored or recorded, for then it may appear not to occur when, in fact, it does. Since some phenomena are created by or made important by recent technology, experience extending much beyond the recent past may have little relevance to them.

The possible differing impact of rare events on an experienced individual and on a national regulatory body may be illustrated by the following. For an assumption that an event could occur at a plant (1) once in 40 y (about once in a working lifetime) or (2) once in 100 y, the probabilities, respectively, are 0.025 and 0.01/plant-year. For an assumption that the same event has an equal and independent probability of occurring at any of 40 plants, the probability that the event will occur in at least one of the 40 plants during any year is for case (1), $1-0.975^{40} = 0.64$; and for case (2), $1-0.99^{40} = 0.33$.

The significance of the frequency decay rate cannot be determined by experience alone. Substantial decays at a high decay rate are rarely experienced. Further, there is very little monitoring of frequency decay on time scales of significance to this problem. For these reasons, an engineer with many years of experience may never have seen a high frequency decay rate. Therefore, by basing his considerations solely on experience, such an engineer may consider the maximum frequency decay rate not to be high enough to cause a problem for the reactor coolant pumps.

4.2.2 Published calculations of frequency decay

Catelli et al.[1] studied the topology of the Northeast Utilities system and determined two ways in which it might break into islands by loss of transmission lines. Their conclusion from this study was that initial frequency decay rates in a range from 0.5 to 1.5 Hz/s could be expected. Based on their system data on line outages and an assumption of statistical independence of events, their computation of the joint probability of simultaneous failure of the two circuits (which would precipitate the event) predicted a failure rate of once in 2000 years. (Since this calculation was based on 8 years of data, and an assumption of statistical independence, and since the northeast blackout did happen--even if conditions have been changed since then--this prediction appears optimistic.) In further studies of loss of generation under conditions where the system was considered virtually isolated from additional outside support, initial frequency decay rates of up to 6 Hz/s were computed. It is emphasized that these results apply only to the system under study.

The results of a series of related studies of frequency decay were published by the Westinghouse Electric Corp.[2-4] The authors of ref. 2 emphasized the determination of limits to generator loading and stated the following conclusions:

1. "The rate at which frequency can decay during a system disturbance is limited. The equations presented in this paper provide a means of calculating the maximum decay rate.

2. "The highest frequency decay rate occurs immediately after the overload is imposed.

3. "Increasing the attempted overload increases the amount by which the generator is actually loaded up to some maximum value. An attempted overload in excess of that value will result in a load bus voltage drop sufficient to decrease the overload and the frequency decay rate.

4. "The voltage regulator action raises the generator terminal voltage and load bus voltage after a few seconds but not enough to modify the rate of decay adversely.

5. "Any load shedding will further decrease the rate of frequency decay after a brief time delay.

6. "The load power factor has a very significant effect on the decay rate.

7. "A uniform distribution of spinning reserve on a power system is very desirable."

The same reference also says, "This paper describes a method of determining the maximum *probable* (emphasis ours) rates at which power system frequency will decay following a disturbance...." The treatment is neither exhaustive nor bounding, but it demonstrates certain limiting characteristics of generators of a standard type. Among the frequency decays computed for various cases, not necessarily realistic, were 3.65, 4.1, and 6.5 Hz/s.

Reference 3, citing what appears to be the same studies as ref. 2, states: "Frequency decay rates up to the maximum *credible* (emphasis ours) decay rate (5 Hz/sec)...." The studies reported in this reference assume a constant rate of frequency decay and compute the thermohydraulic consequences of the assumption. The result is that, for the reactor systems and the constraints considered, a DNBR of at least 1.3 would be maintained if the frequency decay rate is no greater than 6.8 Hz/s. Figure 4.5 in ref. 3 clearly demonstrates a region of not improbable operations where, according to the calculations presented, the maximum frequency decay rate would exceed 5 Hz/s.

Reference 4 carries on the analyses of the electric power grid for other cases, explicitly taking into account units with leading power factor, multimachine islands, and units connected to long, high-capacity transmission lines. One of the significant results presented is the following: "The study concludes that under some conditions, frequency decay rates greater than 5 Hz/s are possible when the unit is operating at rated turbine power...." In one case, a maximum frequency decay rate of 10.9 Hz/s was computed.

All of the foregoing calculations were, and necessarily so in view of the complexity of the problem, specific in many details. Hence, generality cannot be claimed for the results. However, it is apparent that serious and strenuous efforts were made to consider cases that were among the most severe that might be encountered. Results obtained in the more extreme cases considered conform generally with the highest frequency decay rates which we have been able to find recorded from actual operating experience.

4.2.3 Recorded events--the empirical approach

As indicated in the preceding sections, our discussions with persons expert in electric utility operations and our examination of some of the available computational studies on the subject appeared to yield a consensus that maximum credible frequency decay rates were reasonably low, quite possibly low enough to ensure no problem from this source to the reactor coolant pumps. However, some doubts remained, perhaps because some of the calculations indicated a possibility of high frequency decay rates in regions that could not be considered incredibly inaccessible to operations.

We began searching records of events that might have shown significant frequency decay rates. There is a considerable body of writing on the northeast blackout of 1965, in which the highest frequency decay rate reported for that event is about 1 Hz/s.[5] In fact, there was little frequency monitoring equipment in place at that time, which lack continued until recently. In recent years, a few oscillographic recorders were placed in service at selected locations. These are strip chart devices that display one cycle of a 60-Hz frequency over several inches of paper, thus enabling response of the recorder to rapid frequency changes which otherwise could not be resolved with a recorder of a slower response. The oscillographs do not continuously record at high speed on paper; they are tripped *on* when an electric signal indicates that a problem has occurred. The strip chart movement of these instruments is based on timing signals independent of system frequency. Thus, the frequency decays recorded by these instruments show time resolutions sufficient to permit a determination of decay rate in Hertz per second (Hz/s).

Most instruments record frequency traces on coarse time scales (Fig. 2 is one such), and many other recorders provide even poorer resolution. Such recordings permit observation of the total frequency swing, but not its rate. Whether the inertia of such recorders would permit them to show the total swing of an event restored in 5 s is doubtful.

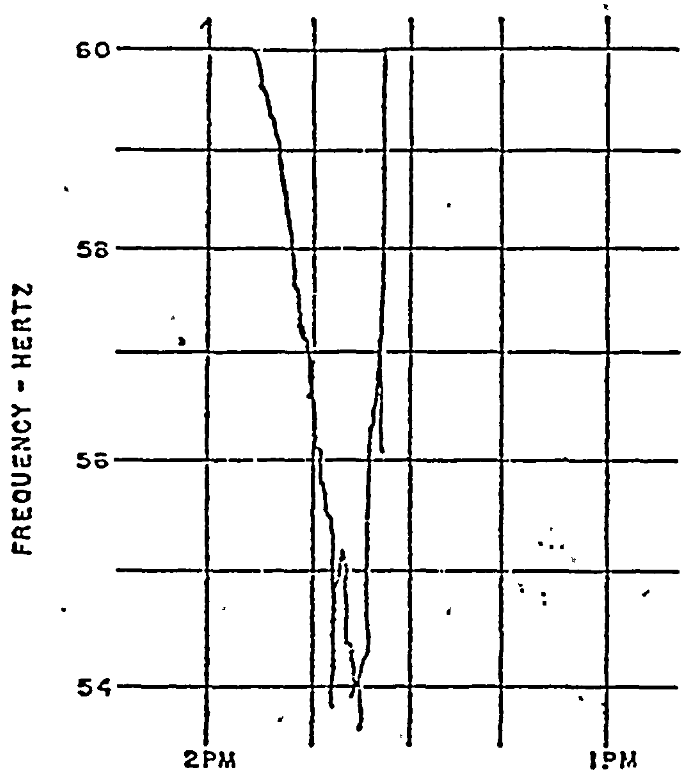

Fig. 2. Frequency of fringe portion of southern system islanding on July 5, 1957.

Recorded frequency data (on a gross resolution time scale) of a major southeastern utility were examined. These data had been recorded during critical periods of the week of January 17, 1977—a period of protracted cold during which the area had experienced its greatest load demand to that time. The frequencies were below 60 Hz, the integrated time error at one point was about 30 s, and the reserves were minimal. At approximately the same time, a large generator had failed in a neighboring utility, causing a total frequency drop of ∿0.1 Hz. Although this experience gives little information on assessment of the maximum credible frequency decay rate, it does give some indication of the stresses on grids and of their inherent strength.

The reporting activity of the Federal Power Commission (FPC) concerning power losses grew following the northeast blackout. Looking for information on frequency decay, we read all quarterly reports of electric power disturbances published by the FPC, numerous topical reports, and reports by utilities to the FPC related to system disturbances. Two documents issued by FPL[6,7] reported frequency decays in their system that exceeded 1 Hz/s. (We found no other reports of a frequency decay rate that exceeded 1 Hz/s.) Figure 3 (from ref. 6) shows a severe frequency drop which occurred on their system June 28, 1974. Figure 4 (from ref. 7) shows the decay of frequency at one bus of the FPL system during the final stages of system collapse in the outage of May 16, 1977.

In a parallel study of loss of offsite electric power at nuclear power plants, we found only one case where frequency decay during an event was noted and reported (ref. 7, already cited).

4.3 Discussion of Recorded Frequency Decays

Figures 3 and 4 bear some discussion to place them in the context of the problem we are considering. As noted, Fig. 4 is a record of the frequency collapse of a subsystem after it had become isolated and had lost all its power generation capability. The power did not drop instantly to zero, because energy was stored in inductive devices. However, as the system parasitically drained off that energy, the rotating pump motors (serving as generators) slowed down, and the line frequency decreased correspondingly. Such an outcome had been foreseen as qualitatively the worst case of frequency decay that might occur, and, in view of the scarcity of recorded information, it is fortunate that it was reported to the FPC. In Fig. 4, the frequency decay rate is 10.7 Hz/s in the interval between 14 and 15 s. This measured decay rate is the largest that we have determined throughout the investigation.

Although Fig. 3 shows a lower decay rate, it nevertheless merits some discussion. The frequency rises to just above 62 Hz, plunges to below 55 Hz, and then recovers. During this disturbance on June 28, 1974, some load was lost in southeast Florida, causing the increase in frequency. Then at >62 Hz, some large generators tripped off on overspeed, causing the plunge in frequency. During the plunge, underfrequency relays acted

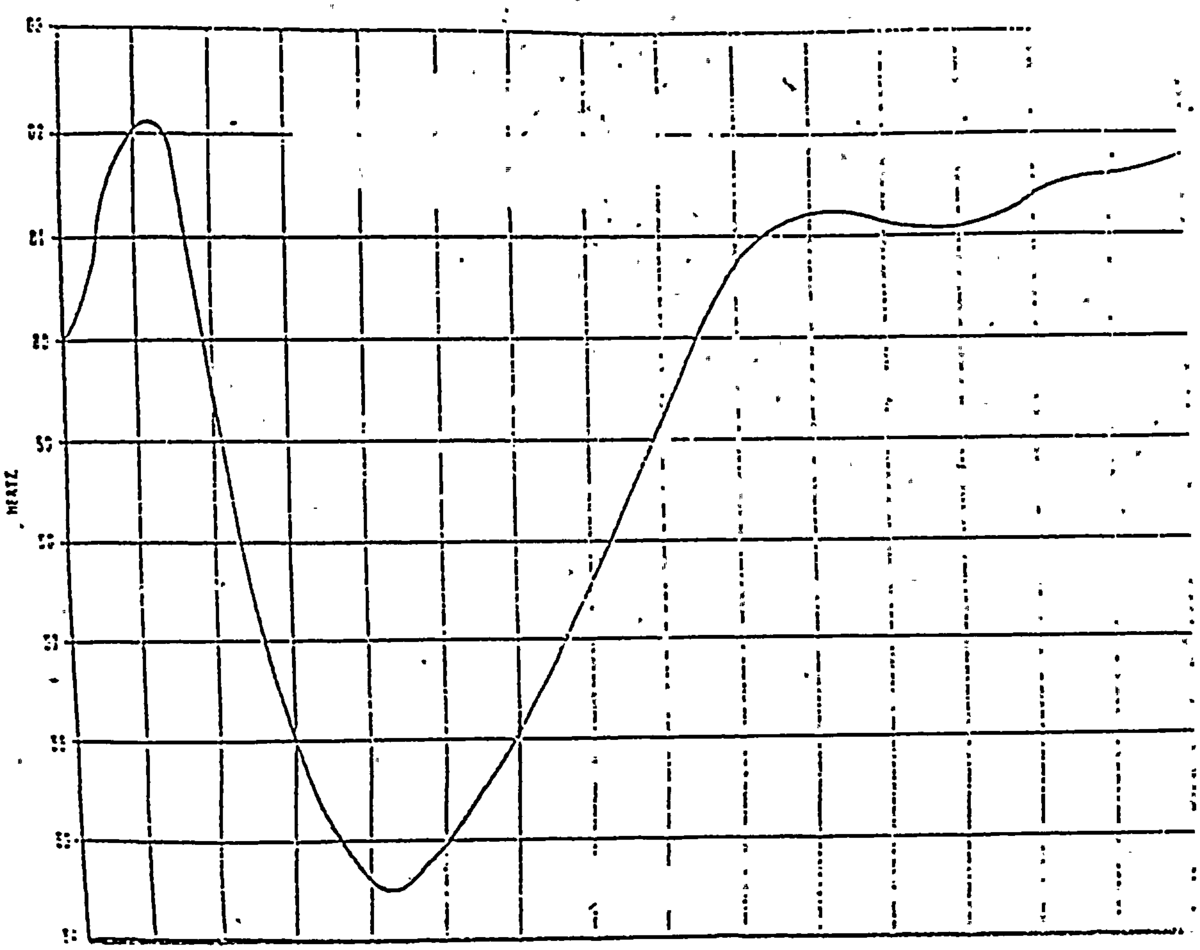

Fig. 3. Florida Power and Light Company, Dade Station frequency disturbance on June 28, 1974.

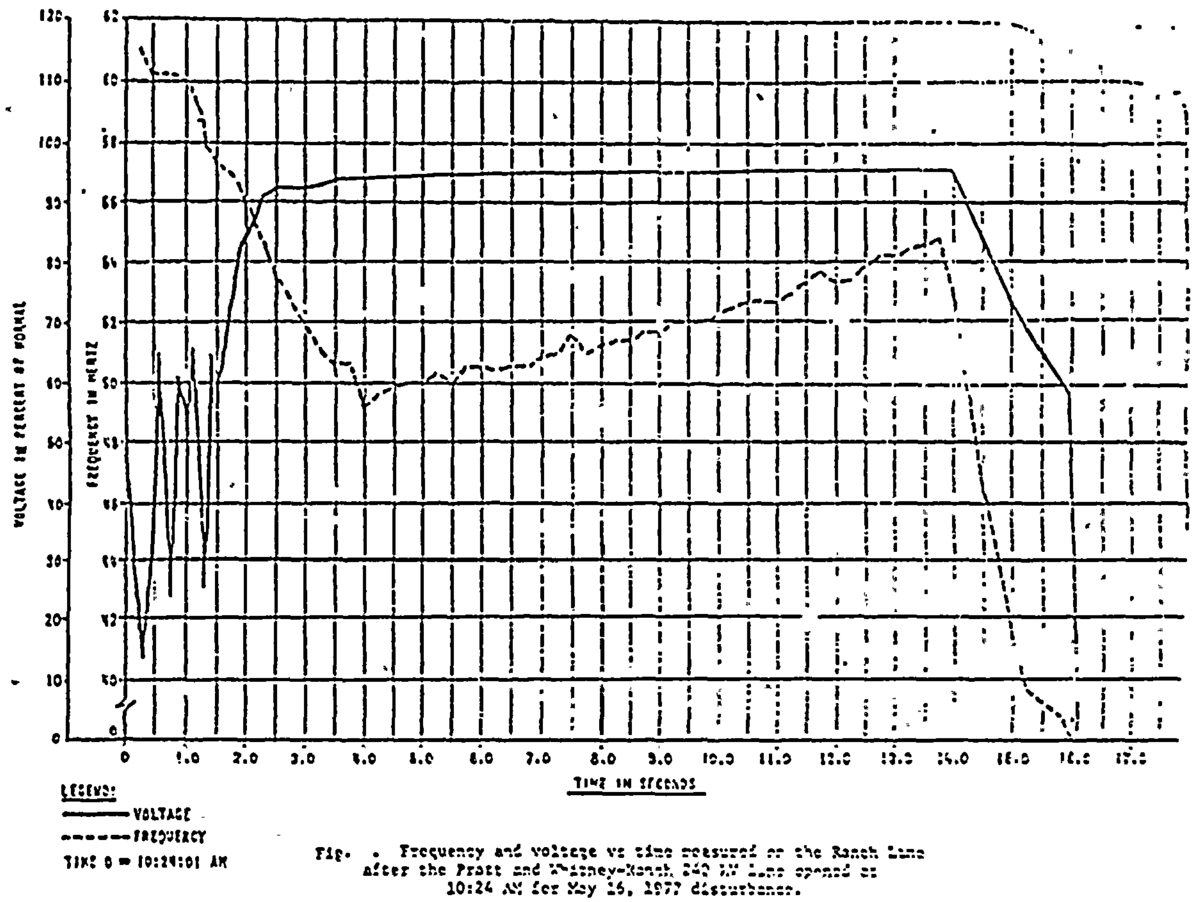

Fig. 4. Frequency and voltage vs time measured on the Ranch Line after the Pratt and Whitney-Ranch 240-kV line opened at 10:24 AM for May 16, 1977, disturbance.

automatically between 59.2 and 58.5 Hz, shedding load and leading to the recovery of the subsystem from 54.5 Hz.

Two important considerations follow from the fact that this decay began at >62 Hz. First, if a PWR plant with reactor coolant pumps had been connected to the bus on which this frequency decay was recorded--and there was not--the initial overspeed to 62 Hz would have added stored energy to the pump-motor system; therefore, in the initial part of the subsequent decay, the pump-motor system would have been returning excess energy to the grid. Second, because the decay started from >62 Hz, extra time was required to reach the load-shedding trip levels distributed from 59.2 to 58.5 Hz, thereby prolonging the duration of the decay.

From these considerations, we believe that it is quite possible that a thermohydraulic analysis of this case might show that it has a severely limited potential for damage to the reactor of the kind under consideration.

4.4 Other Approaches to the Frequency Decay Problem

From our study described in the preceding section, we believe that an assessment of the probability of occurrence of special events that must happen to create serious problems due to frequency decay might support two conclusions: (1) the probability of occurrence of such an event would lie within tolerable limits, and (2) the consequences would be bearable.

An encompassing study of frequency decay would include the following considerations as well:

1. To cause a problem, not only must the frequency decay be severe, but, simultaneously, all reactor coolant pumps must remain tied to the grid, and the nuclear plant generators apparently must be detached from the grid. What is the probability of such joint events?

2. Given the occurrence of such joint events, what DNBR would be achieved, and how much damage would result? In such an evaluation, how loosely is the momentum in the coolant water coupled to the electric grid (includes taking account of effects of pump bypasses and other similar paths.)?

3. Are frequency decays that begin from greater than 60 Hz substantially less troublesome?

Since different vendors of PWRs have determined that 2.3, 3.0, and 6.8 Hz/s are the magnitudes of frequency decay rate their systems can tolerate without exceeding DNB limits, it appears that there are substantial differences either in the systems or in the assumptions made in dealing with the problem. Thus, to develop a basis for a generic resolution of these differences, it appears that the NRC should request the vendors or the operators to provide sufficiently detailed assessments of their plants so that significant differences can be compared and understood. The following information, we believe, would be appropriate for operators of PWR power plants:

1. Assume the following:. the power transmission systems, or fringes of it, have separated; the PWR plant is in a separate segment, all generation in that segment is lost, and the PWR plant generator is the last to shut down. What would be the expected rate of frequency decay as the last generator goes off line and the segment then draws stored energy from on-line inductive devices during its final collapse?

2. How many times during the past 20 years has there been a total interruption of service to customers of this system when the total load was 200 MW or more? Give the time, description, and duration of each such event.

3. Does the utility record line frequencies at any point or points? If it does; what is the largest total frequency drop that has occurred in any time period of 5 s or less? Give a fully detailed description of the event. If the recording equipment does not resolve 5 s, give a detailed description of the largest frequency drops that have occurred in resolved times. If such equipment was operating in any area in which service was interrupted as described in question 2, supply a copy of the record of the final frequency decay in each case.

4. How many reactor coolant pumps does the PWR have? What is the minimum number of pumps that would have to be disconnected from the power grid during a frequency decay rate of 11 Hz/s extending over 2 s to ensure that the system would not exceed DNBR limits during coastdown and changeover to alternative cooling? What DNBR would be reached if all pumps remained connected to the power grid? What damage to fuel, cladding, or other components would result? What breakers or other mechanisms are there for separation of the reactor coolant pumps from the electric power grid? Describe the various ways these mechanisms would be actuated during a frequency decay of the magnitude contemplated.

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1. A. P. Catelli, G. J. Bartels, and G. E. Jorgensen, "Frequency Behavior and Event Prediction of An Electrical Island," Northeast Utilities Service Co., IEEE PES Winter Meeting and Tesla Symposium, New York City, January 25-30, 1976.

2. M. S. Baldwin and H. S. Schenkel, "Determination of Frequency Decay Rates During Periods of Generation Deficiency," Westinghouse Electric Corp., IEEE-PES, San Francisco, July 20-25, 1975.

3. M. S. Baldwin, M. M. Merrian, H. S. Schenkel, and D. J. Venderwalle, "An Evaluation of Loss of Flow Accidents Caused by Power System Frequency Transients in Westinghouse PWRs," Westinghouse Electric Corp., WCAP 8424, Rev. 1 (May 1975).

4. H. S. Schenkel, "Frequency Decay Rate Analysis--Special Considerations," Westinghouse Electric Corp., supplementary material for WCAP 8424, Rev. 1 (May 1976).

5. "Prevention of Power Failures," Advisory Committee Report to the Federal Power Commission, June 1, 1967.

6. "Report on System Disturbance, June 28, 1974," Florida Power and Light Co., July 19, 1974 (to Federal Power Commission).

7. "Report on System Disturbance, May 16, 1977," Florida Power and Light Co., June 29, 1977 (to Federal Power Commission).