Building a Reliable, Robust Power Grid for Present and Future Energy Needs

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Background and Introduction

The United States power grid has experienced an increasingly number of unplanned outages in the last decade. These outages appear to be becoming more significant in recent years. Unplanned outages have occurred in 2011, 2014, 2021 and 2022. The Winter Storm Uri, for example in 2021, in Texas and the South-Central U.S., saw the largest controlled load shedding event in U.S. history, up to that time, with over 20,000 MW of load shed in the Texas ERCOT system alone.

In this event, over 4.5 Million people lost power, some lasting as long as 12 days. It was estimated that over two hundred lives were lost. The costs to the Texas economy was estimated to be between $80 to $130 Billion(1).

Review of 2022 Winter Storm Elliott

Winter Storm Elliott occurred between December 21 and December 26, 2022. During this event, 1702 power generation units in the Eastern Interconnect experienced 3,565 unplanned outages.(1) A number of units had multiple outages from the same or different causes.

At the worst point of the event, there were 90,500 MW of unplanned generating unit outages. Including generation that was already out of service, a total of 127,000 MW generation was not available representing 18% of the US portion of the resources in the Eastern Interconnection.

This situation was of such dire concern that in October 2023, the following report was issued:
Inquiry into Bulk Power System Operations During December 2022 Winter Storm Elliott(1).
FERC, NERC and Regional Entity Staff Report, October 2023
This 167 pg report goes into great detail concerning the massive outages of power equipment following the storms Uri in 2021 and Elliott in 2022.

As a former Professor of Mechanical and Aerospace Engineering, my research laboratory at the University of Virginia concentrated on rotor-bearing dynamics and developing reliable power equipment for NASA, petrochemical and the utility industries. I have worked very closely with both nuclear and fossil fuel utilities.

What has happened to the power utility field is a loss of reliable base power systems. Base power is the energy supplied by stationary oil, coal and nuclear power stations. These are called primary energy sources which operate 24/7 and are insulated from weather conditions.

What has happened over the past years is that the U.S. has lost a considerable amount of reliable base power. For example, many nuclear power plants have been closed down because of fear of accidents. The 2,200 MW San Onofre Nuclear Plant in CA, for example, was worth more than 300 unreliable offshore wind turbines!

A good example of the results of the policy of ending nuclear power is Germany. They have closed all of their nuclear power plants and relied principally on wind power from the North Sea.

Due to unusual weather conditions, with low wind velocities, they had to revert to activating a number of their old coal fired power plants for base energy. As a result, they have the most expensive and unreliable, dirty power in Europe.

Another important source of reliable base power are coal fired power plants. Instead of putting scrubbers and precipitators on these plants to remove particulates and CO2, these plants have been closed down. This represents another great loss of reliable base power.

To replace the loss of reliable base power provided by nuclear, oil and coal-fired power plants, the utility industry has had to resort to the use of 100 MW gas turbines. These gas turbines were designed for topping power and are not robust equipment that can provide reliable power 24/7. During the storms of Uri and Elliott, a large number of these units shut down due to lack of fuel and mechanical difficulties.

Figure 67: Total MW Loss of Incremental Generation Outages, Derates, and Failures to Start (Outaged MW) by Cause, December 21-26, Total Event Area

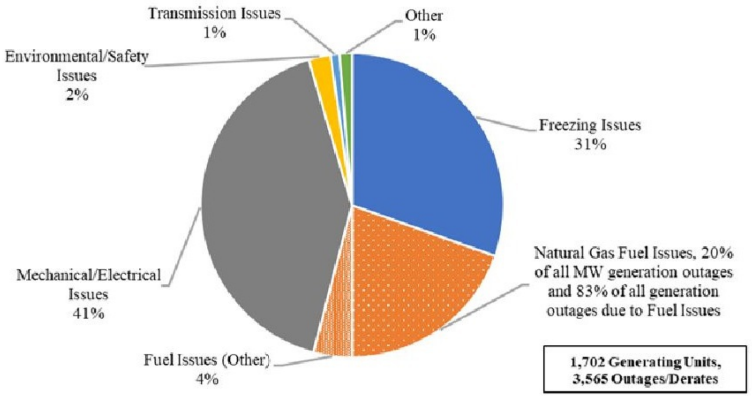

Figure 67 was taken from the Winter Storm Elliott Report of 2022. The figure shows that 1,702 generating units had a total of 3,565 outages or derates.

Note that freezing and natural gas fuel issues played a considerable part in the outages that occurred in winter storm Elliott. This was similar to what happened with the earlier storm Uri when many gas turbine outages occurred due to lack of fuel and freezing issues.

In addition to the problem of providing fuel for these gas turbines, these turbines have a number of significant dynamics problems that can prevent start up and can also cause shut down during operation. Unlike conventional steam turbine-generator systems, which operate at 1,800 RPM or even 1,200 RPM for the larger nuclear units, the 100 MW gas turbines operate at 3,600 RPM.

As such, the second critical speed of these gas turbines fall below the operating speed range. This can cause a problem on start up due to high vibrations in the 3,200 RPM speed range. Another problem with these gas turbines is the requirement for a flexible support under the turbine bearing. This leads to a poorly damped rotor-bearing system which creates problems in balancing and rotor stability. Under full power conditions, the lightly damped turbine may become unstable due to Alford forces acting on the turbine causing subsynchronous whirling.

Figure 68: Generation Outages, Derates, and Failures to Start (MW) by Fuel Type, December 21-26, Total Event Area

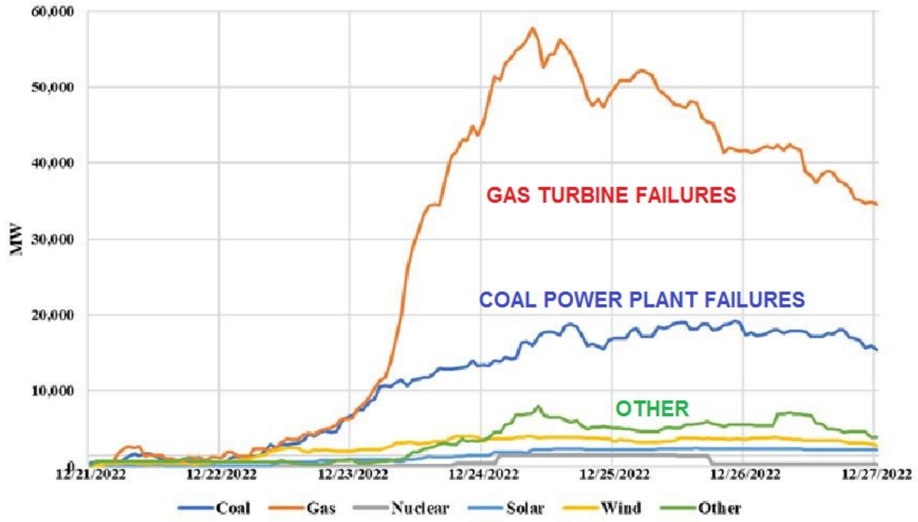

Figure 68 of the Winter Storm Elliott report indicate that peak failures occurred around noon on Christmas Eve of 2022. It appears that approximately 70% of the outage was due to gas turbine failures. Coal fired power plants amounted to 20% of the recorded failures. These failures were attributed to predominantly frozen coal supplies stored externally.

Figure 107: Eastern Interconnection Frequency: December 23, 11:00 p.m. to December 24, 6:00 a.m.

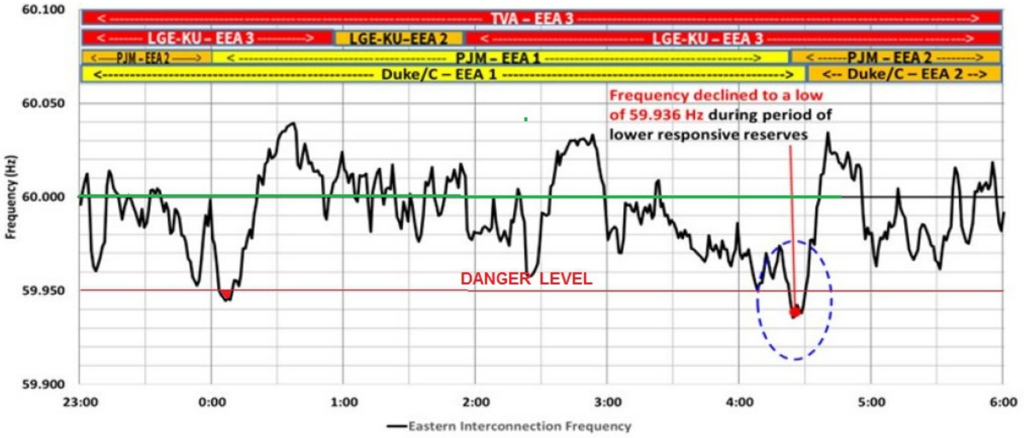

Figure 107 of the Elliott Winter Storm report shows the frequency variation that occurred between December 23 and December 24. The generator frequency of 60 Hz must be maintained within +/- 0.05 Hz to maintain good stability. On the morning of December 24, the frequency dropped to 59.936 creating a serious problem for grid stability.

It should be noted that for synchronous generators to perform effectively, three parameters must be kept in close balance. These parameters are the maintenance of voltage, frequency, and phase relationships between the generators.

Figure 109: PJM Day-Ahead and Actual Hourly MW Wind and Solar Production, December 21 – 26, 2022

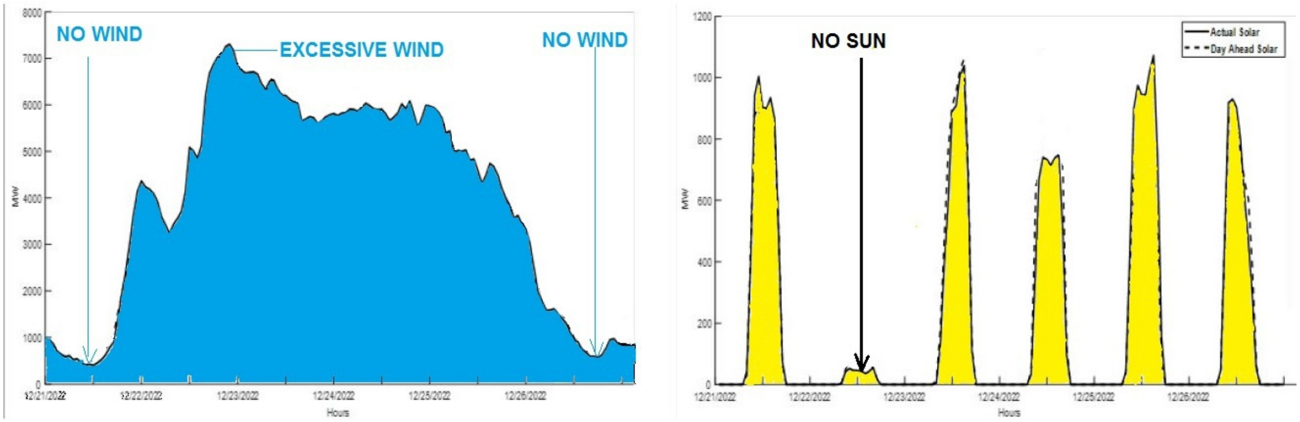

Figure 109 of the Elliott Winter Storm report represents the amount of energy generated by wind and solar during the period of December 21-26, Solar and Wind energy represented approximately 1 and 2% of total energy during that period. As can be seen from the figures on wind and energy generated during that period, the grid operators have no control over the amount and quality of this energy. Considering the strict requirements that land-based synchronous generators must maintain on voltage, frequency and phasing, the energy generated from wind and solar is considered as ***unconditioned, unregulated and unreliable***.

For example, wind energy is generated from variable speed asynchronous generators. As such, it is virtually impossible for them to develop the strict requirements of control of frequency, voltage, and conforming phase that is required in order to properly integrate power with land-based power generators. There is concern by the grid operators that if too much of this energy is forced on the grid, then grid stability will be compromised, and that stationary power equipment such as the turbine-generators, transformers and other electrical equipment may be damaged.

The energy from solar farms presents an entirely different picture. The energy produced by solar farms is DC and an inverter must be used to convert it to alternating current. In conjunction with requiring current converters, battery storage is required for consistent use. The problem with large utility lithium batteries is that the lithium battery fluid is highly flammable. If one cell is damaged, then a runaway battery fire can ensue.

These fires are almost impossible to extinguish since the fires generate internal oxygen to add to the intensity of the fire. To extinguish the battery fire, temperature must be reduced below 500° C. If normal firefighting procedures using water to extinguish a lithium battery fire are used, the water will combine with the battery electrolyte to form HF, a highly corrosive acid which can ***etch glass***!

The grid operators are faced with growing intensity to improve the grid to enable more renewable energy to be added. There is simply nothing that can be done to the grid to make this unreliable energy reliable and compatible with stationary synchronous turbine-generators. An example of this effort to force unwanted energy onto the grid is FERC Order 901 concerning improving inverter characteristics.

Reliability Problems with 100 MW Gas Turbines

In both of the Winter Storms Uri and Elliott, one common characteristic was the extensive failure of the 100 MW gas turbines to perform under winter conditions. In addition to fuel problems, there were a substantial number of mechanical problems which cause these units to shut down.

A number of years ago, because of the problems of the reliability and balancing of these gas turbines, the engineers of Dominion Power approached the Rotor-Bearing Dynamics Research Laboratory of the Univ. of Virginia to analyze in detail, the problems of balancing and stability associated with these gas turbines.

This research led to a 38 page paper, coauthored with John Waite of Dominion Power, entitled

Dynamic Analysis and Field Balancing of 100 MW Utility Gas Turbine-Generators

This paper was presented as the keynote address at the Vibrations Institute Annual Conference in 2016 in Asheville, NC. This paper may be downloaded on ***ResearchGate*** or on our website at ***www.RODYN.com***.

These gas turbines were not designed to be primary suppliers of reliable energy 24/7. Even if great efforts are made to winterize these plants, massive failures of these units can be expected in the future during large winter storms. Reliable base power cannot be achieved using these units for present and future energy demands.

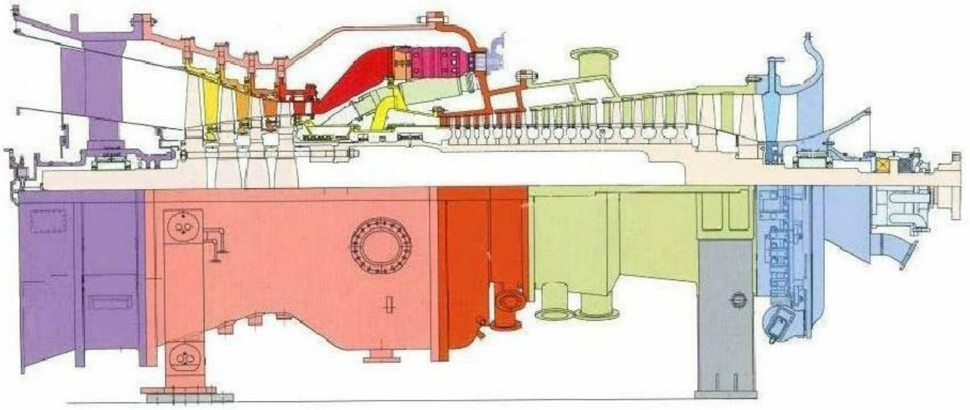

Fig. 1 Schematic Drawing of 100 MW Utility Gas Turbine

Figure 1 represents the cross-section of a typical one hundred MW utility gas turbine.

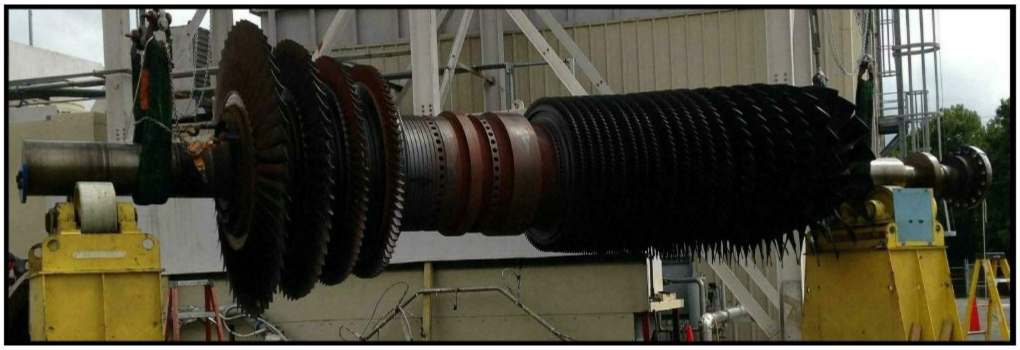

Fig. 2 100 MW Gas Turbine Being Removed For Servicing

Figure 2 represents a typical 100 MW gas turbine being removed for servicing.

Critical Speeds Of a W501D Gas-Turbine Generator

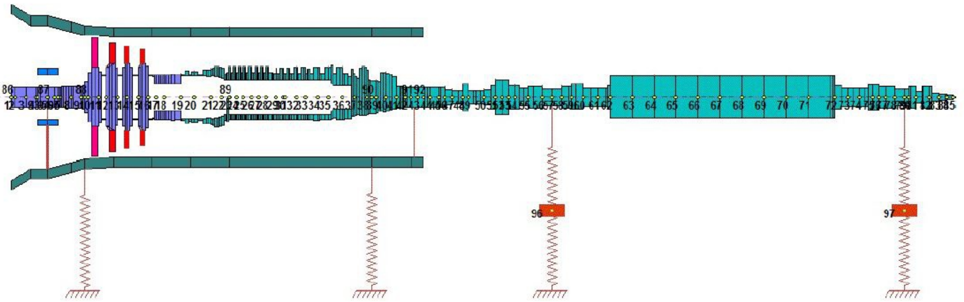

Fig. 11 Computer Model of the W501 Gas Turbine Generator

Figure 11 represents a computer model of a typical 100 MW gas turbine-generator system. What makes the gas turbine uniquely different from conventional steam turbines, is that the casing for the gas turbine is extremely flexible and interacts with the dynamics of the turbine.

Of major significance with the gas turbine is that the tilting pad turbine bearing must be flexibly mounted. This flexible mounting is necessary due to the high temperatures at the gas turbine section. The influence of the flexibly mounted tilting pad oil lubricated bearings is that the flexible support reduces the effective damping of the turbine bearing by over 80%. This results in some drastic dynamics in which the turbine first mode has very light damping and hence may be susceptible to self-excited whirling, due to Alford forces generated on the turbine, under high load conditions.

This self excited whirl motion is not present in conventional steam turbines as the bearings are solidly mounted on very stiff and massive steel casings. Another significant difference between the dynamics of gas turbines and conventional steam turbines is that the steam turbines normally operate at a speed of 1,800 RPM were as the gas turbines are operating at a speed of 3,600 RPM.

Hence with conventional steam turbines, the second critical speed is above the operating speed range. However with the 100 MW gas turbines, the second critical speed is just slightly below running speed. Therefore when the gas turbines are coming up to speed, high unbalance response of the second mode can often prevent the gas turbine from coming online.

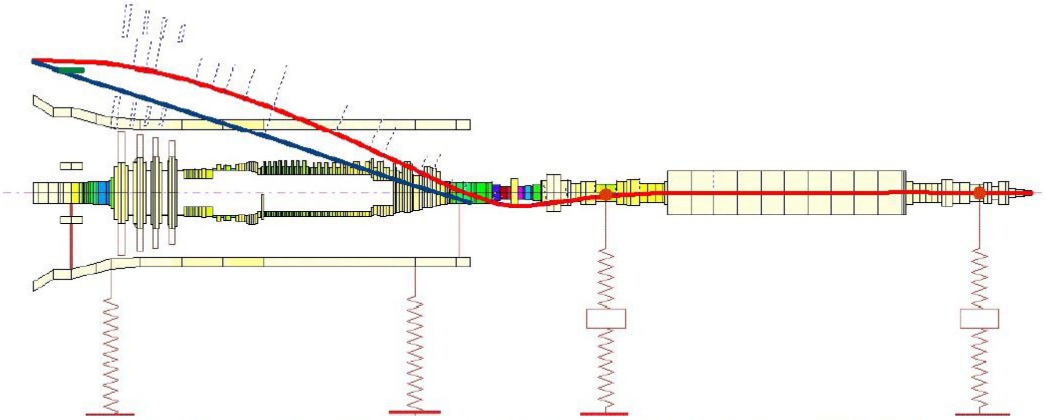

Fig. 12 Turbine-Generator 1st Undamped Mode, M1 = 688 RPM

Figure 12 shows the turbine generator first undamped critical speed. Due to the flexible support under the turbine bearing, high responses are encountered at the turbine location.

2^{nd} Critical Speed Mode of 100 MW Gas Turbine-Generator Systems

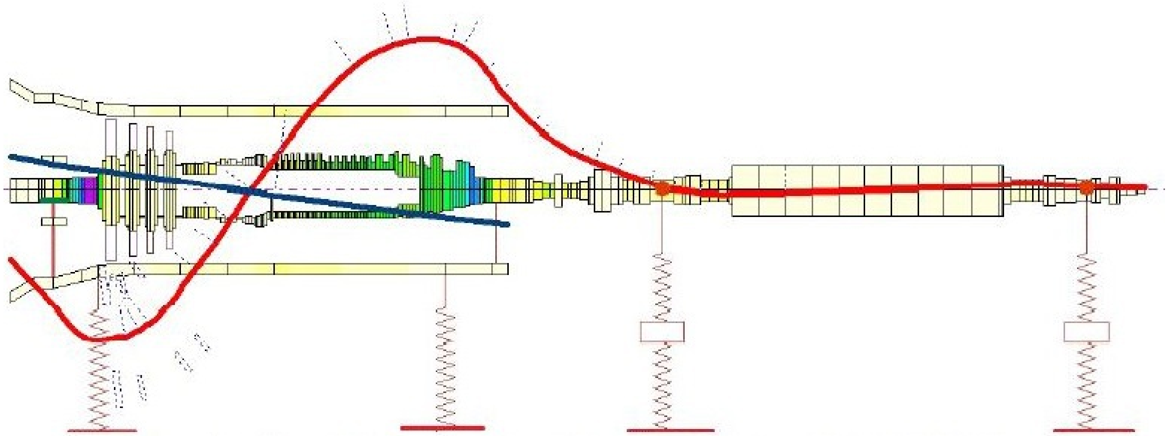

Fig. 17 Turbine-Casing Mode, M6 = 3,164 RPM

Figure 17 represents the second critical speed mode of the gas turbine-generator system. Note that there is a considerable amount of casing motion involved with the second mode. Having the turbine second critical speed to occur just below the operating speed of 3,600 RPM is highly undesirable. High amplitudes of motion, monitored by the turbine vibration probes, may keep the turbine from coming online.

Over a period of time, the gas turbine blades can exhibit wear and erosion, which leads to turbine unbalance. Balancing the turbine to reduce the motion at the second critical speed can be very challenging. To properly balance the second critical speed, requires at least two balancing planes.

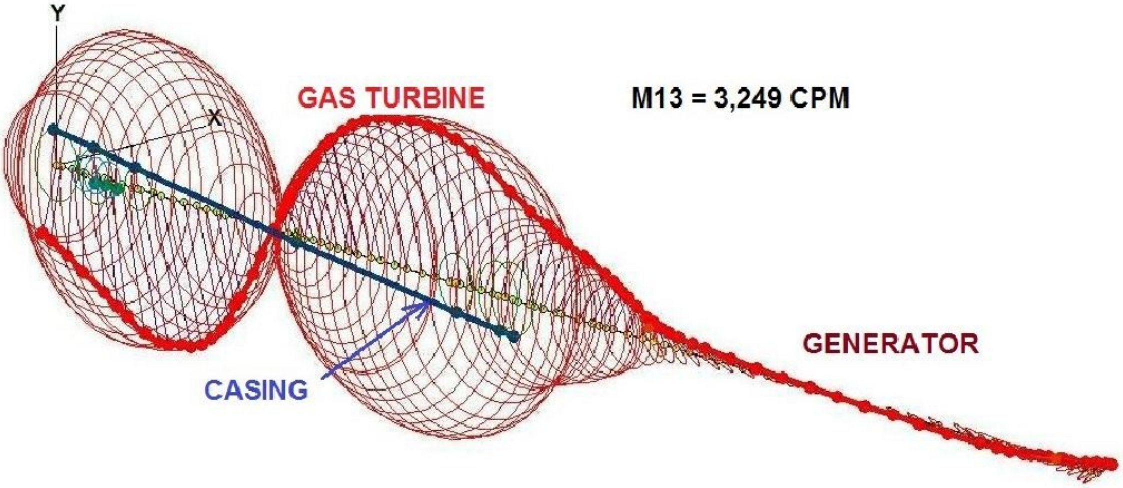

Fig. 28 Gas Turbine Casing Mode M13 = 3249 CPM, log Dec = 0.613

Figure 28 represents a three dimensional representation of the second critical speed, including damping. Note that the casing motion is essentially out of phase to the gas turbine motion. In order to properly balance this particular mode, accelerometers on the casing are required, as well as the relative noncontact displacement probes to measure the turbine motion. This is referred to as a dual probe situation in which the accelerometer motion must be double integrated to obtain the displacement to obtain the absolute motion of the rotor for proper balancing.

Experimental Gas Turbine Vibration Data

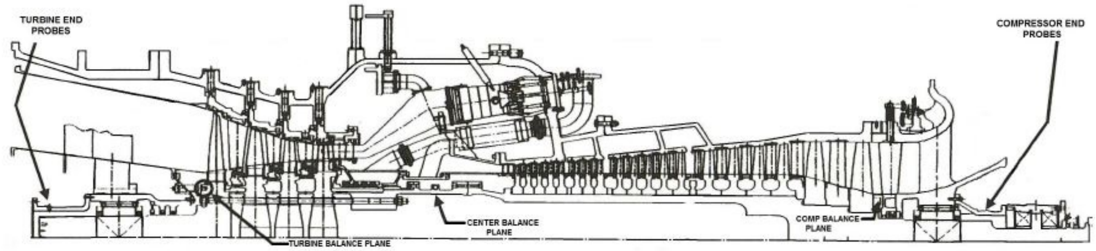

Fig. 29 Gas Turbine Showing Field Balancing Planes and Probe Locations

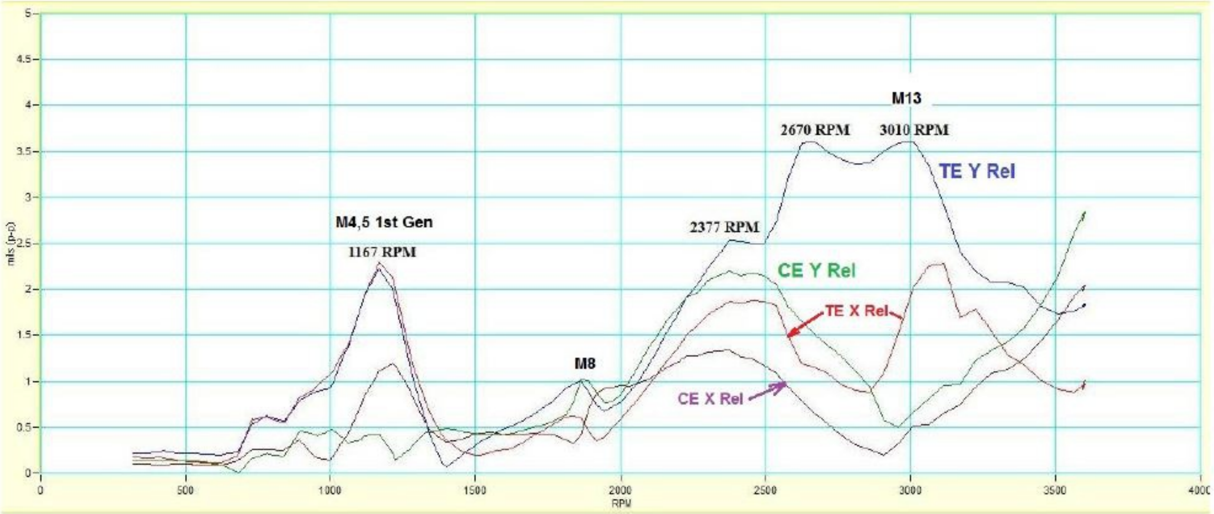

Fig. 30 Relative Probe Measurements at Compressor and Turbine Locations

Figure 29 shows the balancing planes and the probe locations on the turbine. Four probes were installed to measure the horizontal and vertical motions at the gas turbine and compressor locations.

Figure 30, shows the relative probe measurements at the compressor and turbine locations. The largest recorded motion of over 3.5 mils was recorded on the gas turbine vertical probe, TE Y at 3010 RPM. At the operating speed of 3,600 RPM, the largest vibration is at the compressor vertical location, CE Y of 2.8 mils.

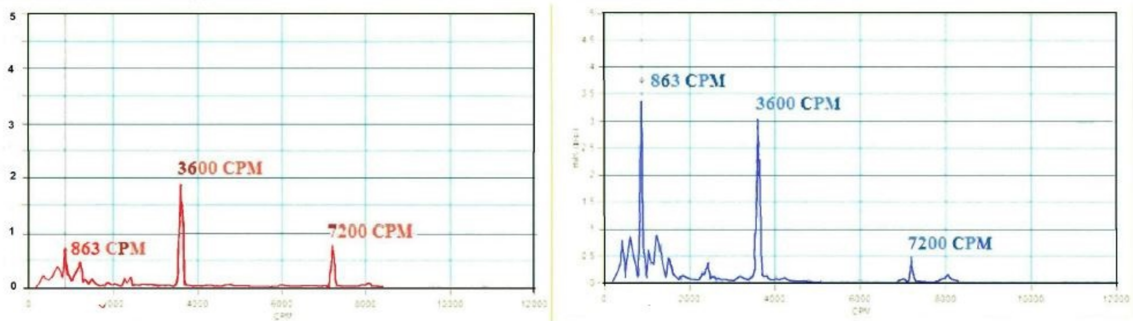

Fig. 32 TE-X Frequency Spectrum At 3600 RPM Showing Subsynchronous Whirling
A. Relative Motion Spectrum B. Absolute Motion Spectrum

Figure 32 shows the relative and absolute horizontal turbine motion at 3,600 RPM. There is high synchronous motion and a substantial amount of subsynchronous whirl at 863 CPM.

Predicted Unstable Gas Turbine Whirl Mode

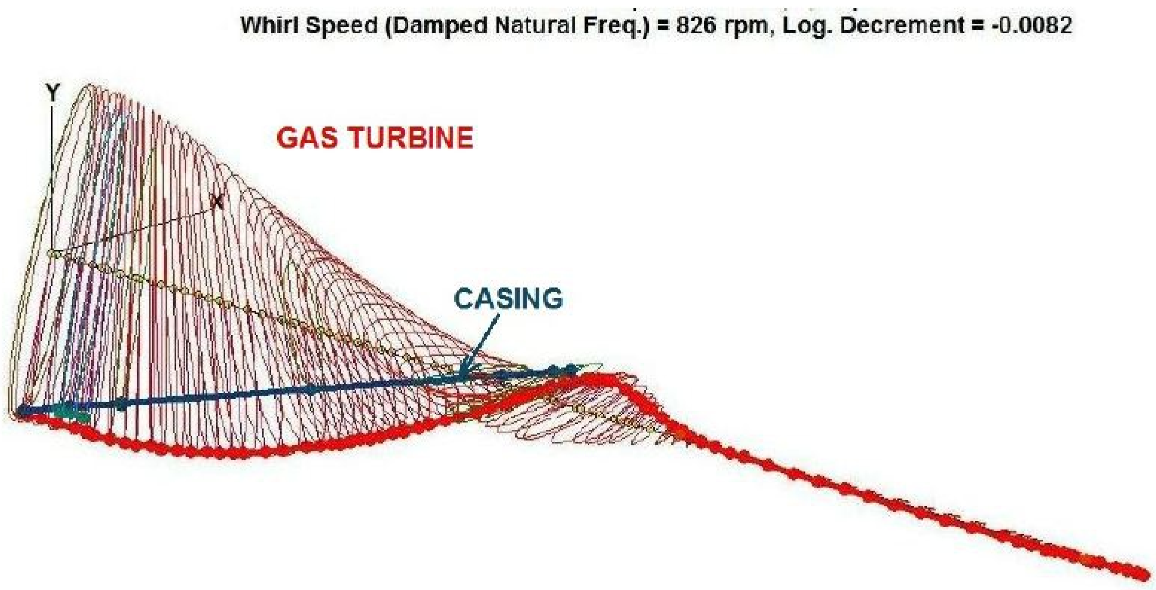

Fig. 33 Unstable Turbine Mode With Aerodynamics Cross Coupling Showing Whirling At 826 CPM, N = 3,600 RPM

Figure 32 of the experimental data shows an unstable whirl mode at 863 CPM with the turbine operating at 3,600 RPM. This whirl mode was generated by the addition of a small amount of aerodynamic Alford cross coupling forces acting on the turbine. Because of the flexible support under the gas turbine bearing, the turbine is lightly damped and hence is susceptible to whirl instability. This phenomena does not occur with steam turbines operating at 1,800 RPM.

Discussion and Conclusions

The utilities have been promoting the use of natural gas turbines for base power. These 100 MW gas turbine units were not designed to produce 24/7 around the clock reliable power. The utilities are exchanging reliable, dirty coal-fired power plants for cleaner, but unreliable natural gas turbine units.

The latest advance towards reliable energy had been the recent approval of new nuclear SMR units such at the Westinghouse AP 300 SMR. These small nuclear units are reliable, safe and would serve as the backbone of base power systems. Studies are also underway on how these small units may replace the boilers of coal-fired power plants so that these plants may be reactivated by using nuclear SMR units as a heat source.

It is also apparent that grid reliability will degrade if large amounts of wind and solar energy are forced onto the grid. This unregulated and unreliable energy could not only disrupt smooth operation of the grid, but it could also damage stationary power equipment.

In summary, with the recently approved nuclear SMR units, there are absolutely no valid reasons to proceed with developing unreliable and expensive wind turbine or solar farms to supply unstable energy to our existing power grids.

The future for reliable, stable energy will lie in the use of recently approved, safe, affordable, and reliable nuclear SMR units such as the Westinghouse AP 300 SMR and similar units.

Resume

Edgar J. Gunter, PhD

Dr. Gunter is a retired Prof. of Mechanical and Aerospace Engineering at the University of Virginia. He received his Mechanical Engineering degree from Duke University and Masters and PhD degrees from the University of Pennsylvania in Engineering Mechanics.

He was employed as a centrifugal compressor design engineer for four years at Clark Brothers, Olean, New York, now a division of Dresser-Rand. Based on his compressor design projects, he was awarded a National Defense Fellowship to pursue the PhD degree in Engineering Mechanics.

During his graduate studies, he received an internship with the SKF Ball Bearing Research Center to study fatigue life of rolling element bearings. In his graduate program, he majored in applied mathematics, vibration and dynamics, fluid mechanics and lubrication theory.

After completing his formal training at the University of Pennsylvania, he assumed the position of Senior Research Scientist at the Franklin Institute Friction and Lubrication Laboratories in charge of the Gas Bearing Division. While at the Franklin Institute, he received a NASA Lewis Research Grant to study rotor - bearing stability. The study was initiated since at that time the Franklin Institute had some of the world's largest digital and analog computers at the Institute. The report on Rotor Bearing Stability was published by NASA as a special CR report and given national distribution. This report formed the basis of his PhD dissertation.

Upon receiving his formal PhD degree, Dr. Gunter was then offered the position of tenured Associate Prof at the University of Virginia. At the University of Virginia, he developed the Rotor Bearing Dynamics Laboratory to assist industry in the development of reliable high-speed rotating equipment.

He has been elected to the following honorary engineering societies of Pi Tau Sigma, Tau Beta Pi and Sigma Xi. He was elected as a fellow of ASME in 1996.

In 2008, Dr. Gunter was awarded the first Jack Frarey Memorial Metal by the Vibration Institute for contributions to the field of rotor dynamics.