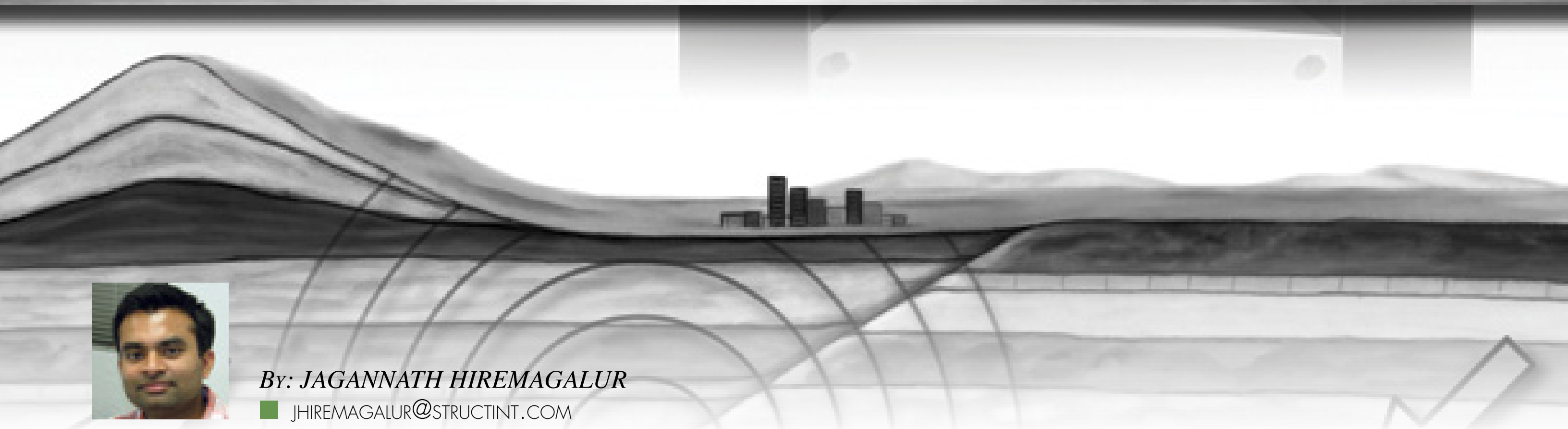
SEISMIC QUALIFICATION ANALYSES OF A SYNCHRONOUS GENERATOR



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Structural Integrity Associates, Inc. (SI) recently completed a seismic qualification analysis of a Gas Turbine Generator (GTG) set enclosure and related components and piping to provide emergency power to PWR. One of the components qualified by analysis was the synchronous generator, which consisted of the following subcomponents:

- Frame
- Bolting to Skid
- Bolts
- Exciter & Permanent Magnet Generator (PMG) support structure
- Gaps specified for housing & rotating components (rotor, exciter & PMG)
- RENK bearing
- Bearings and housings (floating and thrust bearings)

ANALYSIS PROCESS

The seismic qualification analysis is performed in two steps. First, a three-dimensional (3-D) finite element model of the generator is developed and a modal analysis is performed to determine all mode shapes within the frequency range from 0.1 Hz to 100 Hz in order to capture modes within the zero period acceleration (ZPA) frequency. An acceleration of 1g is applied in the vertical direction to simulate gravity. This load case, along with its respective results, are then used.

The second step is to perform a finite element analysis (FEA) of the generator finite element model by applying a single point response spectrum, representing the input floor response spectra for the safe shutdown earthquake (SSE), and combining these results with the gravity (deadweight) analysis results discussed above. The results of these two analyses are added on an absolute sum basis and compared to the stress allowable values in the applicable acceptance criteria provided by the Steel Construction Manual, American Institute of Steel Construction (AISC).

The inputs to a single point response spectrum analysis are mode shapes (eigenvalues) corresponding to different modal frequencies. The bounding safe shutdown earthquakes (SSE) seismic response spectra for the horizontal and vertical directions are used to determine stresses due to seismic excitation. In addition, the maximum horizontal seismic response spectrum is used as the horizontal

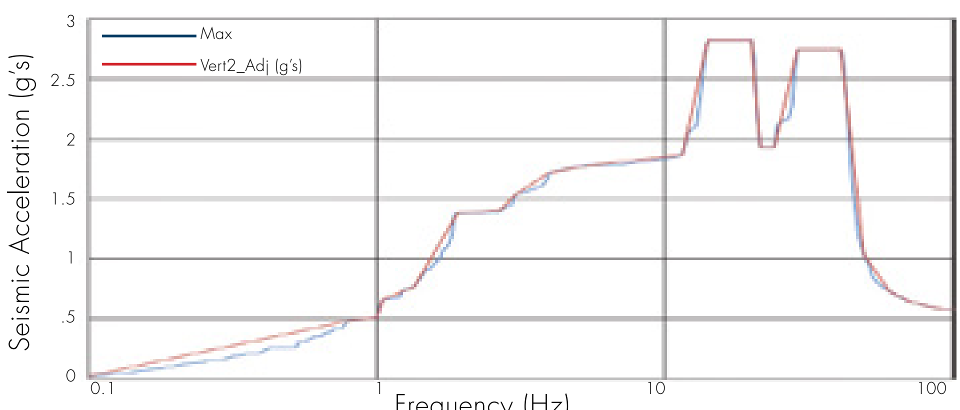
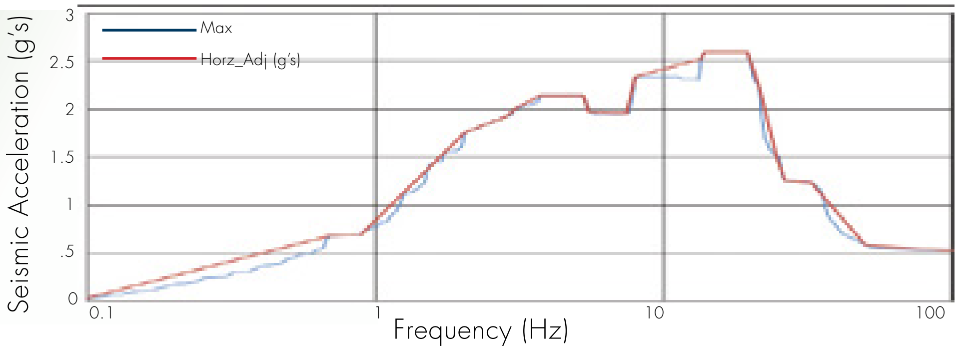


Figure 1. Bounding and Adjusted Seismic Input Response Spectrum Curve for Horizontal Direction, 3% Damping Curve
(Vert2_Adj is the bounding seismic accelerations in the vertical direction)

Figure 2. Bounding and Adjusted Seismic Input Response Spectrum Curve for Vertical Direction, 3% Damping Curve *(Horz_Adj is the bounding seismic accelerations in the horizontal direction)*



spectra for both directions. The spectra used are as shown in Figures 1 and 2.

FINITE ELEMENT MODEL

The finite element model (as shown in Figure 3) is developed and the modal analysis is performed using the ANSYS finite element analysis software package. The Computer Aided Design (CAD) geometry for the synchronous generator was provided by the client and SI imported the model into ANSYS for analysis.

The total weight of the synchronous generator was maintained and the structural stiffness of the un-modeled components was ignored in the analysis. By ignoring the structural stiffness of the un-modeled components, the analysis does not take credit for potential increase in eigen frequency, which is conservative for the seismic analysis.

TECHNICAL APPROACH

Operating and deadweight stresses and seismic acceleration induced stresses were calculated using analysis FEA methods. The resulting stresses due to operating conditions and the combined stresses of operation and seismic conditions are then compared to the allowable stress criteria for the component materials. The acceptance criteria for these evaluations are in accordance with the Steel Construction Manual.

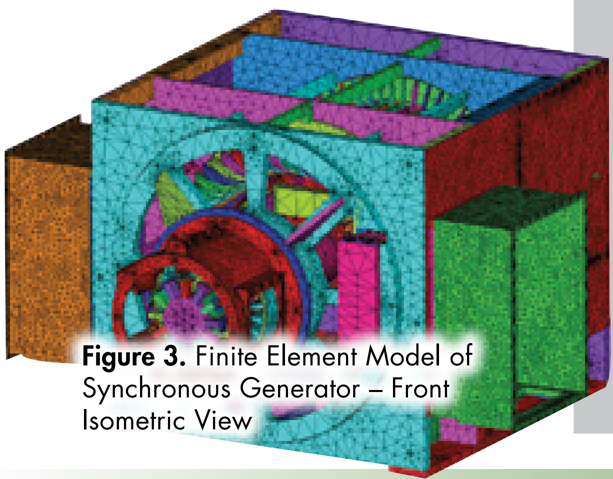


Figure 3. Finite Element Model of Synchronous Generator – Front Isometric View

OPERATING STRESS CRITERIA

For operating and deadweight conditions, the allowable stresses are as follows:

- The allowable stress in tension under operating loads is 60% of the specified minimum yield strength of the most limiting stressed component within the synchronous generator.
- The Steel Construction Manual acceptance criteria is to be applied to average stresses on a member basis and is not intended to provide limits on detailed stress results from numerical analyses. Regardless, maximum stresses at hot spots (peak nodal stresses) are conservatively compared to the allowable stress limits in this evaluation to minimize the need for summing member forces across many sections.
- For those situations where peak stresses cannot be conservatively qualified, through-wall normal stresses are linearized. According to the Steel Construction Manual, combined bending and axial stresses are limited by the interaction formula given below.

$$\left| \frac{f_{ra}}{F_{ca}} + \frac{f_{rbw}}{F_{cbw}} + \frac{f_{rbz}}{F_{cbz}} \right| \leq 1.0$$

where,

f_{ra} = required axial stress at the point of consideration using Allowable Stress Design (ASD) load combinations, ksi

F_{ca} = available axial stress at the point of consideration, ksi

f_{rbw}, f_{rbz} = required flexural stress at the point of consideration using ASD load combinations, ksi

F_{cbw}, F_{cbz} = available flexural stress at the point of consideration, ksi

W = subscript relating symbol to major principal axis bending

z = subscript relating symbol to minor principal axis bending

For those situations where peak stresses cannot be conservatively qualified, the interaction formula can be incorporated in the operating stress evaluation. For the linearized stress case, the allowable bending stress is 0.9*specified minimum yield strength, Fy for a flat plate bending about its minor axis. According to the Steel Construction Manual, the allowable flexural strength is Mn/Ωb, where Mn is the nominal flexural strength and Ωb = 1.67. The allowable flexural strength is (1.5/1.67)*Fy. The 1.5 factor is for converting the plastic section modulus to the elastic section modulus; the section is capable of developing full plastic moment before failing.

- The allowable maximum shear stress for operating loads is 40% of the specified minimum yield strength of the most limiting stressed component within the synchronous generator. The Steel Construction Manual defines the allowable shear strength as Vn/Ω where, Ω =1.67 and Vn is the nominal shear strength. According to the Steel Construction manual, ASD traditionally has used two-thirds of the yield stress as the allowable value (2/3 of 0.6*Fy); thus, the allowable shear stress is equal to 0.4*Fy. Only the membrane (average) component of shear stress is considered for comparison against the stress criteria when it is necessary to extract linearized through-wall shear stresses.

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OPERATING-PLUS-SEISMIC STRESS CRITERIA

For the purpose of the synchronous generator qualification by analysis, the load combinations and stress limit coefficients are obtained from Supplement No. 2 to the Specification for the Design, Fabrication, and Erection of Steel Safety-Related Structures for Nuclear Facilities," (ANSI/AISC N690-1994(R2004).

For operating-plus-seismic loads, the stress limit coefficient for members in tension (normal) shall not exceed 1.6 in members, i.e., allowable tensile stresses are 1.6 times the operating condition allowable stresses. For operating-plus-seismic, the stress limit coefficient in shear shall not exceed 1.4.

ACCEPTANCE RESULTS

Figure 4 shows the exaggerated mode shape (eigenvalue) of the model due to structural modes at the corresponding natural frequency. Figure 5 provides the sum-total of displacements in one of the three orthogonal directions due to the bounding input response spectrum seismic loads (horizontal spectral loading). The stress states in each load direction were then combined by taking the square root of the sum of squares (SRSS) to generate one resultant stress state for seismic. The resulting stresses are used as input for the total stress evaluation. The stress results for the operating loads and the input response spectrum seismic loads were combined by addition on an absolute sum basis.

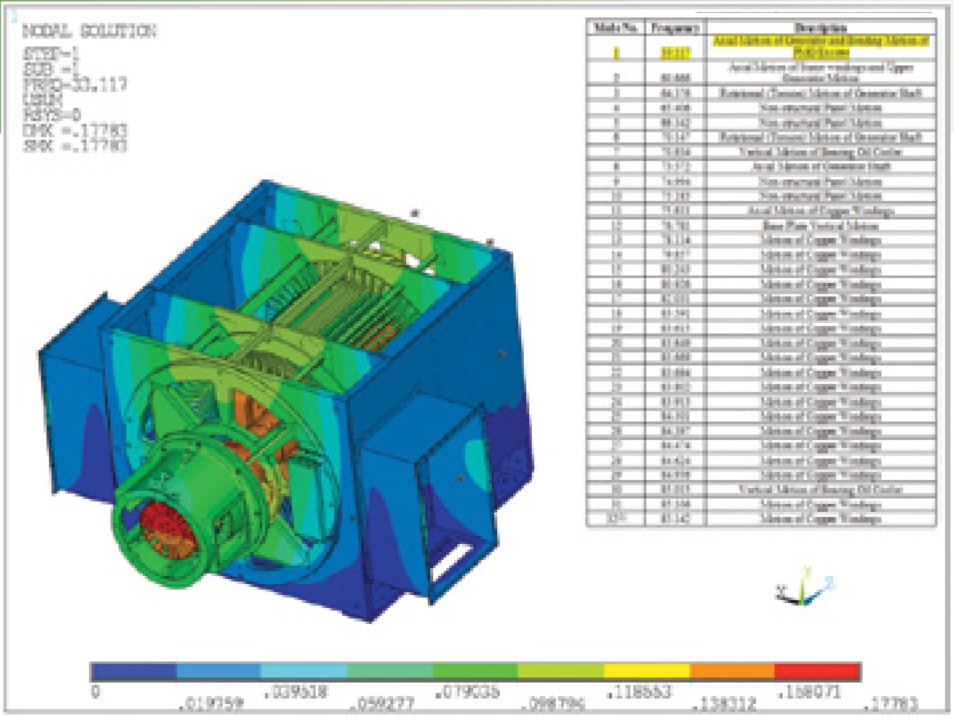

Figure 4. Exaggerated Mode Shape Plot at Natural Frequency of 33.117 Hz

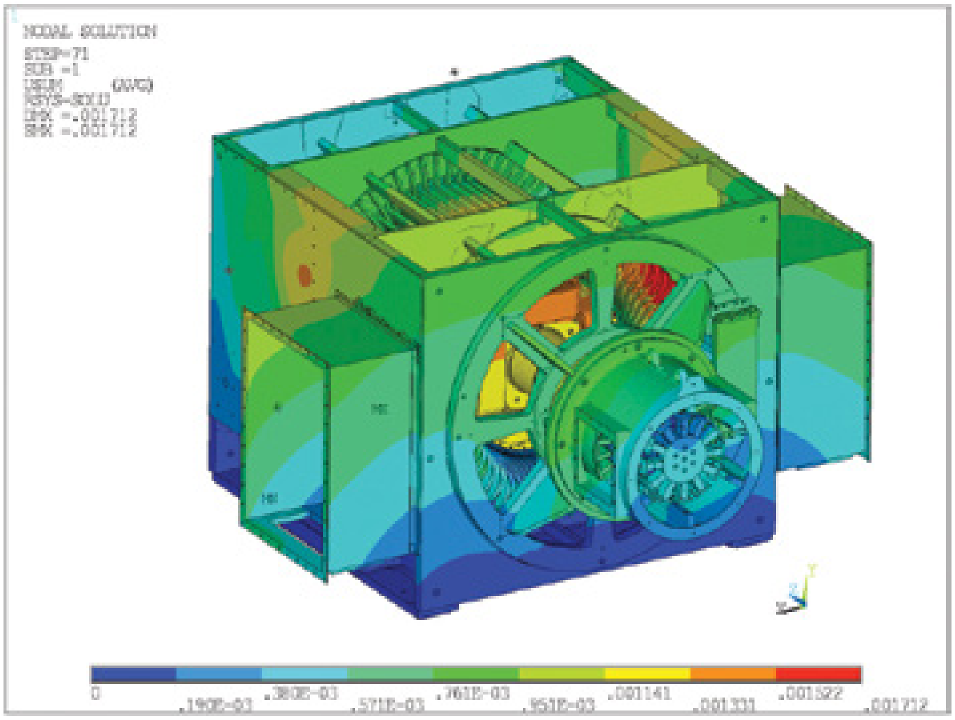

Figure 5. Total Displacement Contour Plot – Horizontal Spectrum Analysis

CONCLUSIONS

The maximum operating stresses, as well as the maximum operating-plus-input response spectrum seismic normal and shear stresses, for the synchronous generator were mathematically shown to meet the allowable stress criteria per the Steel Construction Manual.