Turbo-generator Foundation

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Abstract: This paper deals with the design of a turbogenerator foundation for a thermal power plant. The paper covers the critical aspect in design of turbogenerator foundation with respect to IS 2974 (Part 3)-1992 and other international standards.

Introduction

The turbo-generator forms the heart of a power plant. It is the most vital and expensive equipment of a power plant complex and is generally housed inside a turbo-generator building. A turbo-generator consists of a turbine, generator and other auxiliaries like condenser, pipelines carrying superheated steam etc. Turbo-generator falls under high speed rotary type machines and its capacity varies from 2 MW to 2000 MW. The turbo-generator foundation consists of turbo-generator and its auxiliaries mounted on a table top foundation. The foundation can be either made of steel or RCC. A RCC table top type (fig. 1) foundation are commonly adopted. The top deck, column and bottom raft together constitute the turbo-generator foundation. Sometimes the turbogenerator foundation is mounted on vibration isolator as shown in fig. 2.

FIG 1: TABLE TOP TURBOGENERATOR FOUNDATION
The basic principal of TG foundation remains same compared to other machine foundation.ie,

1) No resonance should occur and hence the natural frequency of foundation system should not coincide with the operating frequency of the machine. The foundation is high tuned when its fundamental frequency is greater than the operating speed or low tuned when its fundamental frequency is lower than the operating speed.

2) The amplitudes of motion at operating frequencies should not exceed the limiting amplitudes, which are generally specified by machine manufacturers.

3) An eccentricity of 3% of base dimension along which the centre of gravity gets displaced may be allowed. The reason to limit eccentricities is to minimize secondary moments that could significantly influence the natural frequencies of the foundation.
INFORMATION NEEDED FOR DESIGN

The following data needs to be provided by machine manufacturer to the designer for the design of TG foundation.

1) Loading diagram showing magnitude and location of static and dynamic loads exerted by machine on its foundation.

2) Speed of turbine and generator

3) Critical speeds of the machine

   Critical speed.

   The angular speed at which the rotating shaft undergoes dynamic instability with increase in lateral amplitude. This develops when the angular speed is in resonance with natural frequency of lateral vibration of shaft. The critical speed concept helps to identify the operational region of rotor bearing system, probable mode shapes and approximate location of peak amplitude.

4) Mass moment of inertia of machine components

5) Drawings showing the embedded parts, openings, grooves for foundation bolts, etc.

6) Piping layout, ducting etc

7) Temperature

8) Allowable amplitude.

Apart from above the following points shall be taken care while designing a turbogenerator foundation.

- The total mass of the frame plus the raft shall not be less than three times the mass of the machine

- The mass of the top deck plus mass of half the length of the column shall not be less than the mass of the supported turbine and its auxiliaries on the top deck.

A minimum gap of 25 mm shall be maintained between top deck of turbo generator foundation and floor of turbine building to avoid transfer of vibration to the floor.

- The clear distance in any direction between adjacent foundations and turbo generator foundation shall be large enough to avoid transmission of detrimental vibration amplitudes through the surrounding. Foundation spacing is intended to ensure that the soil response of adjacent foundations is independent as far as possible. A spacing of 2.5 times the width of the smallest foundation is recommended, because the volumes of soil under stress from adjacent foundations
will not overlap in that case. In such cases vibration isolation pads are to be installed on the adjacent sides of the foundations to avoid transfer of vibration.

- The stress in the soil due to turbogenerator foundation depends not only on the maximum displacement characterizing the vibration, i.e., on the amplitude and frequency, but also on the static pressure to which the soil is subjected. The settlement caused by vibration increases with pressure. Therefore the pressure permitted must be smaller than that permitted for static load. Hence, the stress induced in soil shall not exceed 50% of the allowable bearing capacity of the soil.

**SIZING OF FOUNDATION**

1. **Top Deck**
   The proportioning of the deck is basically governed by the machine manufacturer’s drawing giving the sole plate locations and opening details for the various parts of the machine.

2. **Columns**
   The following guidelines may be followed for column sizing:

   - As far as possible pairs of columns should be provided under each transverse girder
   - Compressive stresses and elastic shortening should be kept uniform in all the columns as far as possible

3. **Base Raft**
   The bottom of the raft shall not be placed above the level as suggested by the geotechnical consultant where the thickness \( t \) of the slab shall not be less than, \( t = 0.07\frac{L}{4.3} \), where \( L \) is the average distance between columns.

**PRIMARY LOAD AND LOAD COMBINATION FOR STATIC ANALYSIS**

Primary loads.

1) **Dead load (DL)**
   Dead load includes self weight of the foundation and dead weight of machine and its auxiliaries. The weight of machine component are supplied by machine manufacturer.

2) **Operation load (OL)**
   The operation loads supplied by machine manufacturer includes friction forces, torque loads, thermal elongation, vacuum in condenser, piping forces etc
a) Torque loads

Forces due to steam in turbine section impose a torque on the stationary turbine casing in the direction opposite to the direction of rotation of rotor. The turbine manufacturer provides this data.

![Torque Diagram](torque.png)

**FIG 3: TORQUE DUE TO NORMAL OPERATION**

b) Vacuum in condenser

In a thermal power plant the mode of cooling the steam in the turbine is done either by air cooled condenser or water cooled condenser. Water cooled condenser are mounted on the base raft whereas the air cooled condenser also called ACC is a separate unit outside the T.G building to which the steam is taken through a separate pipe.

In case of turbine mounted on TG raft, load due to vacuum in condenser needs to be considered. The pressure on the turbine casing is atmospheric and the pressure in the condenser is below atmospheric pressure. The differential pressure between the turbine casing and the condenser results in a suction or a vacuum load transferred to the deck slab through turbine base plates. The magnitude of the vacuum load is significantly large and may be several times the weight of condenser.

c) Frictional load

The heat emitted by pipes carrying superheated steam, circulation of steam through turbine casing itself give rise to temperature gradients between foundation
components causing additional stress on them. Heat buildup in turbine casing and bed plates induces thermal loading on the foundation. The expansion of casing and base plate of the machine relative to the concrete deck results in frictional loads on the slab.

3) Normal machine unbalance force (NUL)

Imbalance in rotating machinery is the common source of harmonic excitation. The cause of this defect may be due to material imperfection, tolerances etc of the rotar leading to centrifugal force in the system and the vibration force is imparted to the bearings as a result of centrifugal forces. Due to unsatisfactory balancing of rotating parts in practice the mass centripod of rotating part does not coincide with center of rotation (refer figure 4). In the course of operation the initial defective balancing may be increased at an alarming rate in consequence of the loosening, corrosion or breakage of the turbine blades. With generators the warming up of the rotar, a displacement of the coils or variation in the material of the rotar may upset the balance. Also the defects of the lubrication system, deficiency of the packing and uneven warming up rotating parts may cause expansion resulting in vibrations which do not follow simple harmonic motion. But undergo complicated changes just like the centrifugal forces produced by them. This fact is however neglected and all mechanical forces are considered as centrifugal ones. For the computation of dynamic effect the data of weight of rotating parts & their point of application is necessary.

FIG. 4.
Where,
m=unbalance mass of rotating part.
e=eccentricity.
$\omega$=angular speed in radian/sec

The coordinate $x$ and $y$ of unbalanced mass are related to angle $\theta$, where $\theta=\omega t$

$X=e\cos\theta$

$Y=e\sin \theta$

The acceleration of mass in $x$ direction is obtained by twice differentiating $x=e\cos \omega t$

$$\ddot{x} = e\omega^2 \sin \omega t$$

Similarly,

$$\ddot{y} = e\omega^2 \sin \omega t$$
The acceleration produces inertia forces \( m \omega^2 \cos \omega t \) and \( m \omega^2 \sin \omega t \). The unbalance mass thus exert harmonic forces in both horizontal and vertical direction. The resultant of the two forces by parallelogram law of forces is given by \( m \omega^2 \).

The unbalance forces are supplied by machine manufacturer. In absence of any data IS2974 recommends the use of formula derived above as given by:

\[
F(t) = m \omega^2 \sin(\omega t + \Phi)
\]

Where \( \Phi \) = phase angle

![FIG 6.](image)

**Calculation of eccentricity \( e \)**

Many rotating machines are balanced to an initial balance quality either in accordance with the manufacturer’s procedures or as specified by the purchaser. As per ISO 1940 balance quality grades G are designated according to the magnitude of the product \( e \omega \) expressed in millimetres/sec. If the magnitude is equal to 6.3 mm/s, the balance quality grade is designated G 6.3.

As per IS 2974 (part 3) turbo-generator and other similar machines are classified under balance grade G2.5. A higher grade is considered for foundation design that is G6.3.

The eccentricity of rotar mass can be obtained from,

\[
G = e \omega
\]
Where $G =$ balance grade in mm/sec
$e =$ eccentricity in mm
$\omega =$ operating speed of machine in radian/sec

Calculation of equivalent static force

a) For machines having frequency more than natural frequency of foundation system.

Equivalent static force $= \text{(Fatigue factor)} \times \text{(Dynamic factor)} \times \text{(Rotating weight)} \times \left(\frac{Ne}{Nm}\right)^2$

Where,

Fatigue factor is taken as 2 as per IS 2974(part 3)
Maximum dynamic factor may be taken as 8
$Ne =$ Speed of machine
$Nm =$ Natural frequency of foundation system.

b) For machines having frequency less than natural frequency of foundation.

Equivalent static force $= \text{(Fatigue factor)} \times \text{(Dynamic factor)} \times \text{(Rotating weight)} \times \left(\frac{Ne}{Nm}\right)^2$

Where Dynamic factor $= \frac{1}{\sqrt{\left(\frac{1}{(Nm/Ne)^2} + \left(\frac{2DNm}{Ne}\right)^2\right)}}$

Where $D =$ dynamic ratio.

4) Temperature loads in foundation (TLF)

a) Uniform temperature

b) Temperature gradient across members.

Load due to temperature changes are generally taken into account by assuming differential temperature between upper and lower slabs and between inner and outer faces of the deck slab. The deck slab is considered as horizontal frame and induced moment due to differential temperature are accounted for.

In absence of any rigorous calculation the moment due to variation in temperature and shrinkage may be calculated by considering the modulas of elasticity reduced to
half and moment of inertia of cracked reinforced concrete to about half to one third of full section.

TABLE A: Values of thermal expansion of concrete.
(for concrete with normal cement content)

<table>
<thead>
<tr>
<th>Type of aggregate in concrete</th>
<th>coefficient of expansion ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>$8 \times 10^{-6}$</td>
</tr>
<tr>
<td>Granite, Basalt</td>
<td>$10 \times 10^{-6}$</td>
</tr>
<tr>
<td>Gravel, quartzite</td>
<td>$12 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

5) Short circuit forces (SCF).
Short circuit induces a severe loading condition on the turbo-generator foundation. A fault of this type occurs when any two of three generator phase terminal are shorted. The short moment affects the foundation via the generator casing in the form of opposite pairs of vertical forces, the moment vector being parallel to shaft axis. The value of short circuit forces is supplied by manufacturer.

6) Loss of blade unbalance (LBL)/Bearing failure load (BFL)

a) LBL
During operation it may happen that one or more blade of the turbine rotar may break. This may increase the unbalance force on the TG foundation. Since the turbo-generator is tripped in such a condition and this force occurs for a short time it is sufficient to check the TG foundation from strength criteria. The machine manufacturer provides this data.

b) BFL
Bending of rotar induces larger unbalance force due to increase in eccentricity. This may be due to differential temperatures, rotar fixed too tightly at both end bearings and improper operation of machine.
7) Seismic loads (SL)

Turbogenerator foundations located in zone of high seismicity are analyzed for seismic loads. Seismic analysis shall be carried out as per IS 1893 (part 4)-2005 which classifies turbo generator foundation in category 2 with importance factor 1.75.

8) Wind Load (WL)

This is usually not considered in the analysis of turbogenerator foundations for in most of the cases the TG foundation is placed inside a turbine building where the wind load is transferred to the ground through the structure itself.

Load combination.

IS 2974 gives the following load combination to be considered for design:

a) DL+OL+NUL+TLF
b) DL+OL+NUL+TLF+SCF
c) DL+OL+TLF+LBL/BFL
d) DL+OL+NUL+TLF+SL

MODELING

The analysis of TG foundation shall be done using a simulated mathematical model of linear elastic properties.

The model for dynamic analysis shall contain the following:

1) Geometry: The foundation shall be modelled as a three dimensional space frame consisting of column, longitudinal beam and transverse beam. However with the availability of commercial software the same can be modelled and analysis using finite element package. The nodes in the model has six degree of freedom, i.e. three translational and three rotational.

2) Support condition: The pressure on the soil under turbogenerator foundation is determined by static load, i.e., by weight of foundation and equipment and hence the TG foundation can be considered to be fixed at base raft level.

3) Mass modelling: Lumped-mass approach shall be used for computing modal masses of the foundation. The machine shall be modelled to lump its mass.
together with the mass of the foundation. The stiffness and damping of the shaft and casing shall generally be disregarded.

4) Material constant:

E value

The actual modulus of elasticity of material for dynamic analysis is one in which irreversible part of deformation need to be separated from total deformation. The modulus of elasticity may be established after determining the relationship between stress and the elastic part of deformation. The natural frequency of turbogenerator foundation depend on the value of dynamic young’s modulus value.

**TABLE B: Range of values of Dynamic young’s modulus as per IS 2974 for concrete.**

<table>
<thead>
<tr>
<th>Grade of concrete</th>
<th>Dynamic young’s modulus (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M20</td>
<td>25590-30000</td>
</tr>
<tr>
<td>M25</td>
<td>28500-34000</td>
</tr>
<tr>
<td>M30</td>
<td>31200-37000</td>
</tr>
</tbody>
</table>

The young’s modulus for static analysis as per IS 456:2000 shall be computed by $5000\sqrt{f_{ck}}$.

5) Damping: Damping is a phenomenon of energy dissipation that opposes free vibrations of a system. Like the restoring forces, the damping forces oppose the motion, but the energy dissipated through damping cannot be recovered. A characteristic feature of damping forces is that they lag the displacement and are out of phase with the motion. The effect of damping in forced vibration reduces the amplitude but does not affect the frequency.

Damping as suggested by IS 2974 is 2% of critical damping under normal operating condition and 5% under emergency condition like blade failure, short circuit, bearing failure etc. The effect of damping may be neglected for free vibration analysis but shall be considered for forced vibration analysis.
6) Moment of Inertia: Rotational inertia may be neglected. Moment of inertia may be determined for section exhibiting no cracks. Shear and torsion deformation may be accounted for.

METHODS OF ANALYSIS

For design of turbogenerator foundation both static and dynamic analysis are carried out.

1) Static analysis.

Static loads are principally a function of the weights of the machine and all its auxiliary equipment. The static analysis of foundation, ie, analysis of forces, moments and displacement of the foundation system shall be based on load combination as discussed above.

a) DL+OL+NUL+TLF
b) DL+OL+NUL+TLF+SCF
c) DL+OL+TLF+LBL/BFL
d) DL+OL+NUL+TLF+SL

Design of individual component of the foundation shall be designed as per IS456:2000.

2) Dynamic analysis

Dynamic loads, which occur during the operation of the machine, result from forces generated by unbalance. The magnitude of these dynamic loads primarily depends upon the machine’s operating speed and the type, size, weight, and arrangement (position) of moving parts within the casing.

Vibration system falls in two major categories: forced and free.

a) Free Vibration analysis

A free system vibrates under forces inherent to the system. The natural frequency (Eigen value) and mode shapes (Eigen vector) of a structure are the parameters that affect response of the structure under dynamic loading. This type of system will vibrate at one or more of its natural frequencies. In this process no external forcing
function is involved, the natural frequency and mode shapes are direct functions of the stiffness and mass distribution of the structure.

Frequency ratio

The frequency ratio is a term that relates the operating speed of the equipment to the natural frequencies of the foundation. Designer requires that the frequency of the foundation shall differ from the operating speed of the equipment by certain margins so as to prevent resonance conditions from developing within the foundation-equipment. The margin can be expressed in terms of $fn/fm$ ratio (natural frequency to operating frequency) which requires that the $fn/fm < 0.8$ or $fn/fm > 0.8$ or in other words the fundamental natural frequency shall be at least 20 percent away from the machine operating speed. However, 50% frequency separation is preferred as IS 2974 (part 3).

If there is a potential for resonance, the designer should either adjust to the foundation size or perform more refined calculations. The size and type of equipment play an important role in this decision process.

High-Tuned System: A high-tuned system is a machine foundation system in which the operating frequency (range) of the machinery is below all natural frequencies of the System.

Low-Tuned System: A low-tuned system is a machine foundation system in which the operating frequency (range) of the machinery is above all natural frequencies of the System.

b) Forced vibration analysis.

Forced vibration is vibration caused by external force being impressed on the body. This type of vibration takes place at frequency of the exciting force, which is an arbitrary quantity independent of the natural frequency of the system. When frequency of the exciting force and the natural frequency coincide, a resonance condition is reached and dangerously large amplitudes may result.
FIG 7: CHART SHOWING STEPS INVOLVED IN DYNAMIC ANALYSIS OF TURBOGENERATOR FOUNDATION
VIBRATION MEASUREMENT

Amplitude

The basic goal in the design of a machine foundation is to limit its motion to amplitudes that neither endanger the satisfactory operation of the machine nor disturb people working in the immediate vicinity (Gazettes 1983). Allowable amplitudes depend on the speed, location, and criticality or function of the machine. The amplitude serves as an important parameter in computing the vibration measurement.

The vibration limits applicable to the machine are normally set by the equipment manufacturer. The limits are usually predicated on either limiting damage to the equipment or ensuring proper performance of the equipment. The normal criterion limits vibration displacements or velocities at the bearings of the rotating shaft. Excessive vibrations of the bearings increase maintenance requirements and lead to premature failure of the bearings.

ACI 20351.3R (04) and DIN 4024 suggests that when the equipment manufacturer does not establish vibration limits, ISO 10816-Part 2 may be referred.
MISCELLNEOUS

1) Transient vibration.

When the natural frequency of the foundation is lower than the operating speed, the maximum dynamic forces at the starting or stopping will be significant for the foundation. Turbine are started gradually in order to secure the “starting time” necessary to start the machine and usually this process takes 20 to 40 minutes. The “stopping time” may be even longer than the starting time which is of the order of 40 to 60 hindering this process the rotary of the machine will rotate within +5 percent of all frequency for 1 to 2 min. With deep under tuning a resonance may therefore occur for a few minutes because the natural frequency may coincide with the speed. And shall be given due care even thought it is of transient nature.

2) Dynamic soil structure interaction (DSSI)

For large capacity turbogenerator foundation consideration may be taken for dynamic soil structure interaction so as to avoid any risk to the foundation during earthquake/machine induced load. Ignoring the soil stiffness in the overall response and treating it as a fixed base problem the dynamic response of structure may not be the solution to the actual behavior of the foundation system. Using Dynamic Soil-Structure Interaction this gap can be bridged by coupling conventional techniques applied in structure and soil dynamics together to understand the overall response of the structure and the supporting soil medium system.

The two classes of problems under which dynamic soil structure interaction plays a significant role are

• Foundation systems subjected to vibration from turbogenerator, i.e., from the machine
• Foundation systems subjected to earthquake.

Soil dynamics deals with engineering properties and behavior of soil under dynamic stress. For the dynamic analysis of machine foundations, soil properties, such as Poisson’s ratio, dynamic shear modulus, and damping of soil, are generally required.

a) Dynamic shears modulus or shear wave velocity

Dynamic shear modulus is the most important soil parameter influencing the dynamic behavior of the soil-foundation system. Together with Poisson’s ratio, it is used to calculate soil impedance. The dynamic shear modulus represents the slope of the shear stress versus shear strain curve. Most soils do not respond elastically to shear strains; they respond with a combination of elastic and plastic strain. For that reason, plotting shear stress versus shear strain results in a curve not a straight line.
The value of dynamic shear modulus varies based on the strain considered. The lower the strain, the higher the dynamic shear modulus.

b) Poisson’s ratio

Poisson’s ratio which is the ratio of the strain in the direction perpendicular to loading to the strain in the direction of loading is used to calculate both the soil stiffness and damping. Poisson’s ratio can be computed from the measured values of wave velocities traveling through the soil. These computations, however, are difficult. The stiffness and damping of a foundation system are generally insensitive to variations of Poisson’s ratio common in soils. Generally, Poisson’s ratio varies from 0.25 to 0.35 for cohesionless soils and from 0.35 to 0.45 for cohesive soils. If no specific values of Poisson’s ratio are available, then, for design purposes, the engineer may take Poisson’s ratio as 0.33 for cohesionless soils and 0.40 for cohesive soil.

c) Damping value of soil

Damping is a phenomenon of energy dissipation that opposes free vibrations of a system. Like the restoring forces, the damping forces oppose the motion, but the energy dissipated through damping cannot be recovered. A characteristic feature of damping forces is that they lag the displacement and are out of phase with the motion. Damping of soil includes two effects—geometric and material damping. Geometric, or radiation, damping reflects energy dissipation through propagation of elastic waves away from the immediate vicinity of a foundation and inelastic deformation of soil. It results from the practical infinity of the soil medium, and it is close to viscous in character. Material damping reflects energy dissipation within the soil itself due to the imperfect elasticity of real materials.

Generally this type of analysis is carried out using software like GT STRUDL.

3) Shaft Alignment

Shaft connects the turbine and the generator may be flexible or rigid.

a) Flexible

A rotating shaft of a machine which has a first lateral natural frequency which is lower than the rotating speed.

b) Rigid

A rotating shaft of a machine which has a first lateral natural frequency which is more than the rotating speed.

If the shaft is flexible, then with increase in the operating speed a slight imbalance in the rotating mass can induce significant dynamic load on the shaft and also the overall deformation of the soil, raft and the frame. This may lead to a phenomenon which is known as the bowing/bending of the turbine shaft which may reduce the operating efficiency of the turbine.
References.


8) DIN: 4024 (Part - 1), 1988: Machine foundations – Flexible structures that support machines with rotating elements

9) ACI 351.3R (04): Foundations for Dynamic Equipment
