IS 2974 (Part 3) : 1992
(Reaffirmed 1995)

भारतीय मानक

मशीन की नींवों के डिजाइन और संरचना – रीति संहिता

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(दूसरा पुनरीक्षण)

Indian Standard

DESIGN AND CONSTRUCTION OF MACHINE FOUNDATIONS — CODE OF PRACTICE

PART 3 FOUNDATIONS FOR ROTARY TYPE MACHINES (MEDIUM AND HIGH FREQUENCY)

(Second Revision)

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Foundation Engineering Sectional Committee, CED 43

FOREWORD

This Indian Standard was adopted by the Bureau of Indian Standards, after the draft finalized by the Foundation Engineering Sectional Committee had been approved by the Civil Engineering Division Council.

The installation of heavy rotary machines, namely, steam turbo-generators, turbo-compressors and blowers, involves design of their foundations taking into considerations the vibration characteristics of the foundations system. While many of the special features relating to the design and construction of such machine foundations are guided by the manufacturers, still a large part of the details shall have to be according to certain general principles of design covering machine foundations. This code of practice for design and construction of machine foundations (IS 2974) is being published in parts. This part lays down the general principles for frame foundations for rotary machines of medium to high frequencies. The other parts of this code are:

IS 2974 Code of practice for design and construction of machine foundatians:

Part 1 : 1982 Foundations for reciprocating type machines

Part 2 : 1980 Foundations for impact type machines (hammer foundations)

Part 4 : 1979 Foundations for rotary type machines of low frequency

Part 5 : 1987 Foundations for impact type of machines other than hammers (forging and stamping press, pig breakers, drop crusher and jolter)

In the design and construction of foundations for rotary machines, a proper coordinations between the different branches of engineering, including those dealing with erection and commissioning is essential.

Coordinated efforts by the different branches would result in satisfactory performance, convenience of operation, economy and a good general appearance of the complete unit. The main unit with all its auxiliaries and adjacent piping must be provided for, when making the foundation plans and all the details should be well worked out, before going ahead with the design.

This standard first published in the year 1967 and subsequently revised in 1975. This revision has been prepared, based on a numbers of comments received on this standard, keeping in view the current design practices followed in India and abroad. The sizes and capacities of turbo-generators have increased (up to 500 MW) since the last revision of the code. There have been fundamental changes in the design philosophy of turbogenerator foundations, for example use of slender columns, long and flexible top decks, etc. With the advent of powerful computers and finite element analysis computer programmes the use of three-dimensional space frame models for static and dynamic analysis has become common in design offices. The code has been made more relevant to design office use. Aspects such as preliminary sizing of the foundations and loading combinations are expected to be useful to the less experienced designers.

For large sized foundations with complex structural arrangement, it has been observed that two-dimensional plane frame models are not possible to use. For such foundations three-dimensional space frame model is recommended for analysis.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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1 SCOPE

1.1 This code is primarily meant for designing framed type foundations for turbo-generators machinery. However, the provisions of this code may be used suitably for other machine foundations of similar types, for example, foundations of turbo-compressors, boiler feed pumps, etc.

1.2 The following classification shall apply to machines based on their operating speeds:

Medium frequency	25 Hz $< fm <$ 50 Hz
High frequency	$\geqslant$ 50 hz

2 REFERENCES

2.1 The Indian Standards listed in Annex A are necessary adjuncts to this standard.

3 TERMINOLOGY

3.0 The common terminology used in structural dynamics and machine foundation design is given below for reference. For a more comprehensive list of terms, refer to IS 2974 (Parts 1 and 2).

3.1 Natural Frequency

The dynamic property of an elastic body or system by which it oscillates repeatedly from a fixed reference point when the external force is removed.

3.2 Free Vibration

Vibration process of a system excited initially, which may be in the form of initial displacement or velocity, but no more time-varying force acting on it.

3.3 Forced Vibration

Vibration process of a system which is caused by external time-varying loads acting on it.

3.4 Damping

Damping is dissipation of energy in a vibrating system.

3.5 Resonance

Resonance of a system in forced vibration is a condition when any change, however small, in the frequency of excitation causes a decrease in the response of the system.

3.6 Mode of Vibration

In a system undergoing vibration, a mode of vibration is a characteristic pattern assumed by the system in which the motion of every particle is simple harmonic with the same frequency. Two or more modes may exist concurrently in a multi-degree freedom system.

4 NOMENCLATURE OF FOUNDATION COMPONENTS

4.0 The following nomenclature shall apply to the components of the foundation in this code (*see* Fig. 1).

4.1 Top Deck

The top portion of the machine foundation consisting of transverse and longitudinal beams.

4.2 Transverse Beams

The members that support the turbine-generator that are transverse to the axis of the machine.

4.3 Longitudinal Beams

The members that support the turbine-generator that are parallel to the axis of the machine.

4.4 Columns

The vertical members that support the top deck.

4.5 Base Mat

The part of the foundation which supports the columns and rests on soil/piles.

4.6 Foundation

The entire structure, including the deck, columns and mat.

5 ISOLATION FROM ADJOINING STRUCTURES

The foundation structure shall be isolated from the main building and also from other structures in the plant. An air gap shall be provided between the foundation and adjoining structures at all levels above the base mat to avoid the transfer of vibrations to the adjoining structures.

6 NECESSARY DATA

6.1 Machine Data

The following data shall be made available to the designer by the machine manufacturer (*see* Fig. 2):

a) Loading diagram of the machine showing the location, magnitude and direction of all loads including dynamic loads;

b) Speed of the machine;

c) Critical speeds of the machine;

d) Outline dimensions of the foundation;

e) Mass moment of inertia of the machine components;

f) Details of inserts and embedments;

g) Layout of piping, ducting, etc, and their supporting details;

h) Temperatures in various zones during operation; and

j) Allowable displacements at the machine bearing points during normal operation.

6.2 Geotechnical Data

Investigation of the site where the foundation is to be located shall be done to evaluate the following parameters:

a) Allowable bearing pressure/pile capacities.

b) In-site dynamic soil properties as per IS 5249 : 1992.

7 LOADING ON THE FOUNDATION

The following loads shall be considered for the foundation design (*see* Annex B):

a) Dead loads which include the self weight of the foundation and dead weight of the machine;

b) Operation loads supplied by the machine manufacturer which include friction forces, power torque, thermal elongation forces, vacuum in the condenser, piping forces, etc;

c) Unbalance forces during normal operation;

d) Temperature forces caused by uniform temperature change and gradient temperature;

e) Short circuit breaker;

f) Loss of blade unbalance forces/bearing failure load;

g) Seismic forces; and

h) Erection loads.

8 SIZING OF THE FOUNDATION

8.1 The preliminary sizing of the various elements of the TG foundation are to be done to arrive at a foundation configuration which will need least changes after detailed analysis and design.

It is convenient and preferable to provide the same soffit level for all the girders from the point of view of design and detailing.

8.2 The geometric layout of the foundation, the shape of the girder cross sections and columns shall be arranged, as fast as possible, symmetrically with respect to the vertical plane passing through the longitudinal axis of the machine.

8.3 Sizing of the 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.

While fixing the depth of the girders the following guidelines may generally be used:

Girders Supporting the Turbine:

Clear span-to-depth ratio = ranging from 2 to 3

Depth to width ratio = ranging from 1 to 3

Girders Supporting the Generator:

Clear span-to-depth ratio = ranging from 2.5 to 3.5

Depth to width ratio = ranging from 1 to 1.5

8.4 Sizing of Columns

The following guidelines may be followed for column sizing:

a) As far as possible pairs of columns should be provided under each transverse girder;

b) Compressive stresses and elastic shortening should be kept uniform in all the columns as far as possible; and

c) The first two natural frequencies of column with its top and bottom ends fixed shall be away from the operating frequency of the turbo-generator by at least 20 percent.

8.5 Sizing of Base Mat

The base mat shall be sufficiently rigid to preserve the shaft alignment. Following are some guidelines for the base mat sizing:

a) The mass of the machine plus top deck,

b) The ratio of the bending stiffness of the base raft and largest columns in the transverse direction should be at least two, and

c) The thickness of the base raft should not be less than 0·07 $L^{4/3}$ in which L is the average of the two adjacent clear spans. This is applicable to rafts supported directly on soil. This shall not be used for piled foundations.

8.5.1 The guidelines given in **8.5** shall be used for the initial sizing of the raft. The final raft thickness, however, would depend on the design forces.

8.6 As far as possible, the foundation shall be so dimensioned that the resultant force due to the weight of the machine, the deck, intermediate slabs (if any) and the base mat together with the weight of the columns passes through the centre of gravity of the base area in contact with the base mat. In cases, where small eccentricities are unavoidable, an eccentricity of up to 3 percent of the base dimension along which the centre of gravity gets displaced may be allowed.

9 STRUCTURAL ANALYSIS

9.1 Modelling

The analysis shall be done using a simulated mathematical model of linear-elastic properties. For turbo-generator foundations of more than 100 MW capacity, a three-dimensional space frame model is recommended. The modelling should take into account the basic characteristics of the system, that is, mass, stiffness and damping. Special attention is required while idealing the points of excitation. The model should simulate the vibration characteristics of the machine foundation system to a sufficient degree of accuracy (*see* Fig. 3).

For smaller foundations (for example, turbo-generator foundations of less than 100 MW capacity) with a regular framing arrangement, plane frame models may be used in the transverse and longitudinal direction.

9.1.1 The following points shall be considered while constructing the model for dynamic analysis:

a) The foundation shall be modelled as a three-dimensional space frame in which the columns and beams are idealised as 3-D beam elements with six degrees of freedom at each node. Slabs and walls, if present, may be modelled using thin shell (plate bending) elements. The columns shall be assumed to be fixed at the base, disregarding the base mat.

b) Nodes shall be specified to all bearing points, beam-column junctions, mid-points and quarter points of beams and columns and wherever the member cross-sections change significantly. Generally, the number of modes specified on any member should be sufficient to calculate all the modes having frequencies less than or equal to the operating speed.

c) 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.

d) Uncracked sections may be used for calculating moments of inertia of the members. The rotational inertia may be disregarded. Shear rigidity shall be considered.

e) Young's modulus shall be computed as per IS 456 : 1978. ($E = 5\ 700\sqrt{fck}$) for static analysis. For dynamic analysis the following range of elastic modulus may be used:

Grade of Concrete	*Dynamic Elastic Modulus* N/mm^2
M 20	25 590 – 30 000
M 25	28 500 – 34 000
M 30	31 200 – 37 000

f) Damping shall be assumed to be 2 percent of critical damping under normal operating loads. A higher damping of 5 percent may be used under emergency loads like blade failure, short-circuit, bearing failure, etc.

9.2 Free Vibration Analysis

Free vibration analysis shall be carried out to calculate the natural frequencies and mode shapes of the foundation. The highest natural frequency calculated should be at least 10 percent higher than the operating frequency of the machine. Damping may be neglected for the purpose of free vibration analysis.

9.2.1 *Frequency Criteria*

The following frequency criteria shall be checked:

The fundamental natural frequency shall be at least 20 percent away from the machine operating speed.

that is, $fn < 0.8\,fm$

or

$fn > 1.2\,fm$

where

fn = fundamental natural frequency of the foundation, and

fm = operating speed of the machine.

However, it is preferable to maintain a frequency separation of 50 percent.

9.3 Forced Vibration Analysis

Forced vibration analysis shall be performed at the operating speed and also at frequencies corresponding to certain selected modes for transient resonance. The calculated displacement shall be checked against the specified criteria.

9.3.1 *Forcing Function*

Generally, the unbalance forces are furnished by the machine manufacturer at each bearing location under different operating conditions.

A sinusoidal forcing function of the form

$$F(t) = F_0 \sin(\omega t + \phi)$$

shall be used for analysis. In the absence of data from the manufacturer the unbalance forces may be derived from the balance quality grade of the machine (*see* Annex C).

9.4 Seismic Analysis

Response spectrum analysis shall be carried out as per IS 1893 : 1984. At least the first five modes shall be considered for mode superposition.

9.5 Static Analysis

A detailed static analysis of the foundation shall be performed to ensure that the foundation carries all the loads safely. The same model which has been used for dynamic analysis may be used for static analysis.

9.5.1 *Load Cases*

a) Dead loads (DL)

b) Operating loads (OL)

c) Normal machine unbalance load (NUL)

d) Temperature loads in the foundation (TLF)

   1) Uniform temperature change

   2) Temperature gradients across members

e) Short circuit forces (SCF)

f) Loss of blade unbalance (LBL) or bearing failure load (BFL)

g) Seismic loads (SL)

9.5.2 *Loads Combinations*

a) Operating condition

   DL + OL + NUL + TLF

b) Short circuit condition

   DL + OL + NUL + TLF + SCF

c) Loss of blade condition/Bearing failure condition

   DL + OL + TLF + LBL/BFL

d) Seismic condition

   DL + OL + NUL + TLF + EQL

10 SOIL-STRUCTURE INTERACTION

The effects of soil-structure interaction on the dynamic response of the TG foundation may be ignored under steady state dynamic loading. However, if the TG foundation is located in zones of high seismicily, soil-structure interaction shall be considered for seismic analysis. No soil-structure interaction need be considered for static analysis and it is sufficient to model the foundation fixed at the base raft level.

11 BASE MAT ANALYSIS

The base mat may generally be modelled with plate bending elements or as a grillage of beams. The soil or piles beneath the base raft shall be idealised as spring elements.

11.1 The bearing pressure on soil or the load on the heaviest loaded pile shall not exceed 80 percent of the net allowable bearing pressure or the safe load capacity of piles respectively.

12 DESIGN

12.1 Working stress method as per IS 456 : 1978 shall be used.

12.2 Increase in Permissible Stresses

Where stresses due to either earthquake, short-circuit or loss of blade unbalance forces/bearing failure loads are combined with those due to dead and permanent load, the permissible stresses as specified in IS 456 : 1978 may be increased by 25 percent.

12.3 Fatique Factor

A fatique factor of 2 shall be used for the dynamic forces caused by normal unbalance.

12.4 Grade of Concrete

The following grades of concrete shall be used:

Top deck	:	M 20 or higher grade
Columns	:	M 20 or higher grade
Base mat	:	M 20 or higher grade

For turbo-generator foundations of capacities higher than 100 MW, the minimum grade of concrete for the end columns shall be M 25.

12.5 Reinforcement Steel

12.5.1 Mild steel bars conforming to IS 432 (Parts 1 and 2) : 1982 or high yield strength deformed bars conforming to IS 1786 : 1985 may be used.

12.5.2 Minimum dia of reinforcement bars used as main reinforcement shall be 12 mm.

12.5.3 *Minimum Reinforcement*

Beams of top deck

Top and bottom	:	0.25 percent (each) of gross sectional area
Sides	:	0.1 percent gross sectional area on each side

Columns

Longitudinal reinforcement	:	0.8 percent of gross sectional area

Base mat

Top and bottom	:	0.12 percent (each) of gross sectional area in each direction
Intermediate layer	:	Shrinkage reinforcement of 0.06 percent in each direction if the raft thickness is more than two metres

12.5.4 The maximum spacing of the reinforcement bars shall not exceed 300 mm and the minimum spacing shall not be less than 150 mm.

12.5.5 Splices in the reinforcement bars shall be staggered and shall be given in the compression zone as far as possible.

12.6 Concrete Cover

Minimum clear cover to reinforcement shall be 50 mm for top deck and columns and 100 mm for the base mat.

12.7 Reinforcement Detailing

Care should be taken while detailing to facilitate ease of concreting. The clear spacing between bars should be at least 5 mm more than the sum of aggregate size and the largest bar diameter used.

12.8 Construction Joints

12.8.1 The base mat shall be cast in a single uninterrupted operation. Properly designed construction joints shall be provided between the base mat and columns and between columns and the top deck. Construction joint may also be provided approximately at the mid-height of columns if the length of the column exceeds 8 metres.

12.8.2 The top deck shall be cast in a single uninterrupted operation.

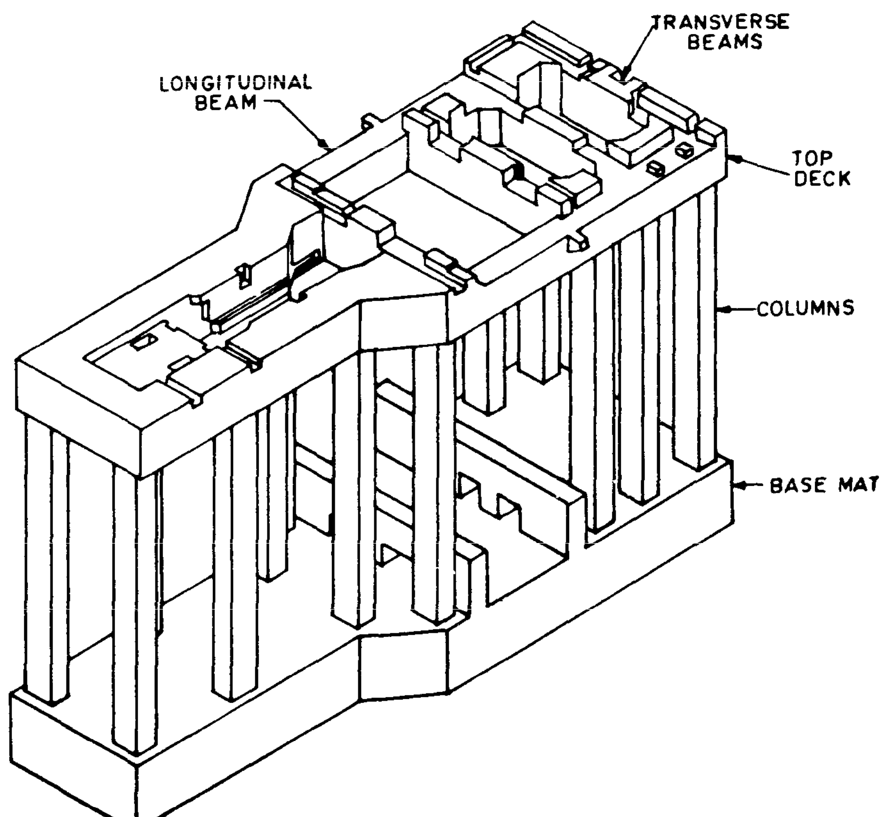

FIG. 1 TYPICAL FRAMED FOUNDATION FOR A TURBO-GENERATOR

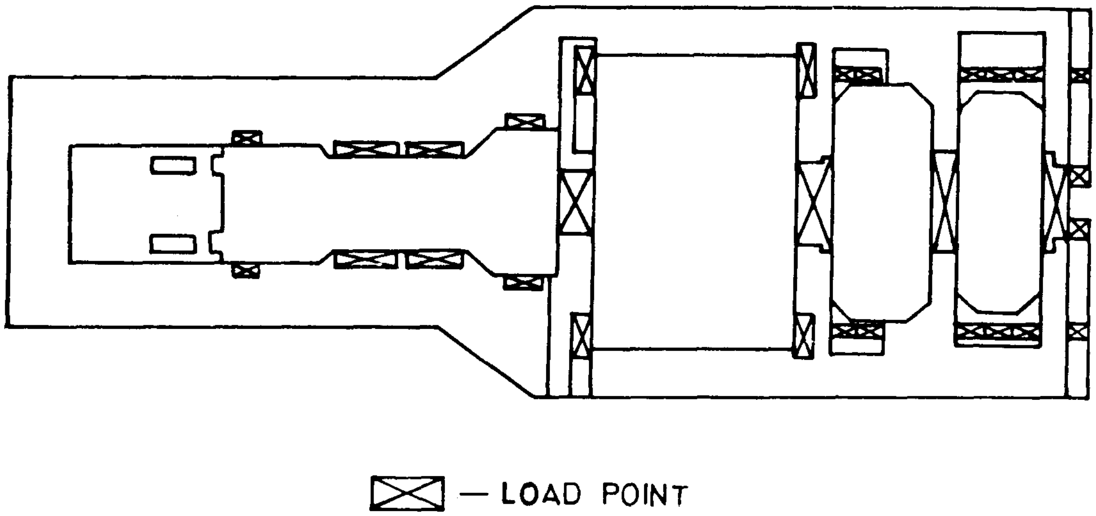

FIG. 2 TYPICAL LOADING DIAGRAM

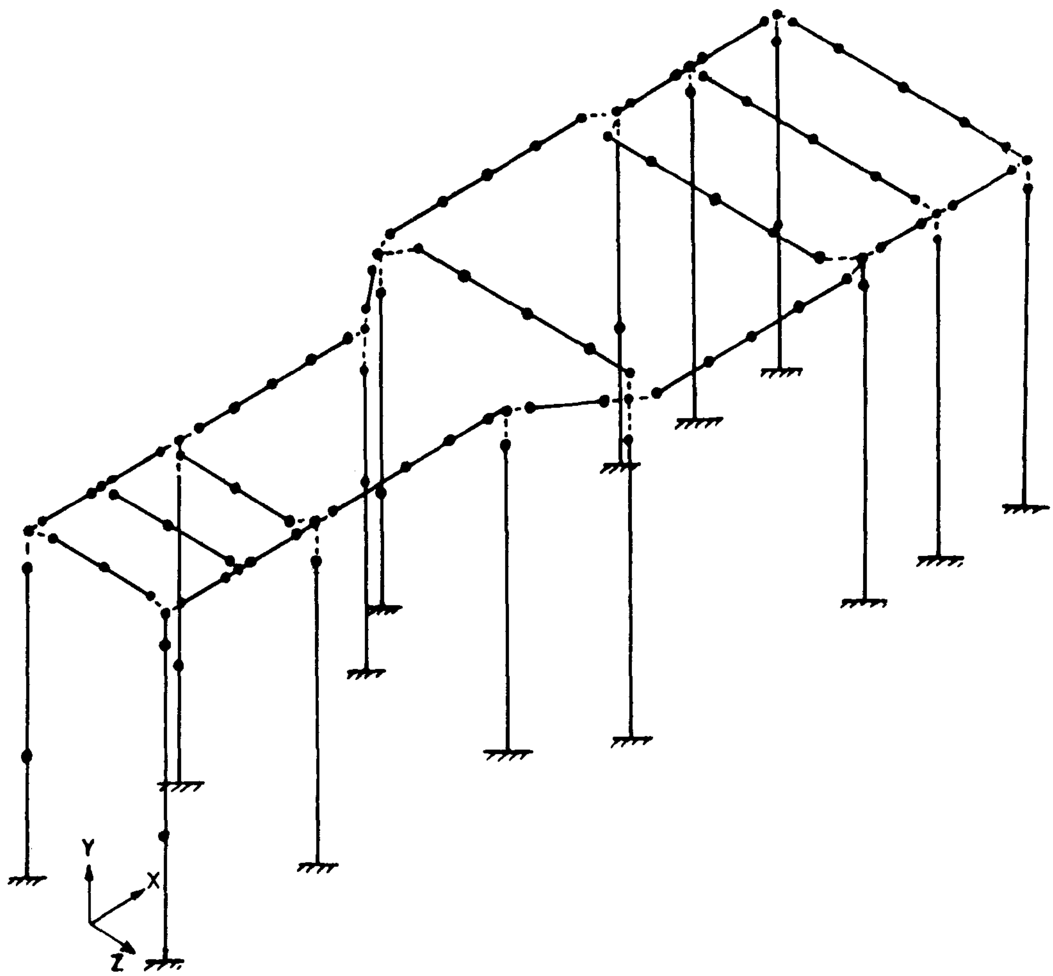

FIG. 3 SPACE FRAME MODEL OF THE FOUNDATION SHOWN IN FIG. 1

ANNEX A
(*Clause* 2.1)

LIST OF REFERRED INDIAN STANDARDS

IS No.	*Title*
432 (Part 1) : 1982	Specification for mild steel and medium tensile steel bars and hard-drawn steel wire for concrete reinforcement: Part 1 Mild steel and medium tensile steel bars (*third revision*)
432 (Part 2) : 1982	Specification for mild steel and medium tensile steel bars and hard-drawn steel wire for concrete reinforcement: Part 2 Hard-drawn steel wire (*third revision*)
456 : 1978	Code of practice for plain and reinforced concrete (*second revision*)
1786 : 1985	Specification for high strength deformed steel bars and wires for concrete reinforcement (*third revision*)
1893 : 1984	Criteria for earthquake resistant design of structures (*fourth revision*)
2974 (Part 1) : 1982	Code of practice for design and construction of machine foundations: Part 1 Foundations for reciprocating type machine (*second revision*)
2974 (Part 2) : 1980	Code of practice for design and construction of machine foundations: Part 2 Foundations for impact type machine (hammer foundations) (*first revision*)

ANNEX B
(*Clause* 7)

ABNORMAL LOADING

B-1 LOSS OF BLADE UNBALANCE

The turbine rotor is balanced dynamically to enable smooth operation of the machine. An emergency condition can occur when one or more turbine blades break loose from the rotor, which would impose a large dynamic force on the foundation at the bearing locations. The forces corresponding to a massing last-row blade for each turbine section are supplied by the machine manufacturer in the form of unbalance forces or equivalent static forces. Since the turbo-generator is tripped in such a condition these forces occur for a short time required for the coasting down time of the machine. It is sufficient to check the foundation for strength under these forces.

B-2 SHORT CIRCUIT FORCE

When a line-to-line or line-to-ground short circuit occurs at the generator terminal, it imposes a huge torque on the TG foundation. The short-circuit moment has the form (*see* Fig. 4).

$$M(t) = Ae^{-t/0.4} \sin \omega t - Be^{-t/0.4} \sin 2\omega t + Ce^{-t/0.15}$$

where

ω = angular frequency of the mains.

A, B, C = coefficients specific to generator design.

The forcing function is generally supplied by the Machine Manufacturer. It is advisable to perform a dynamic analysis of the foundation. Sometimes, only the equivalent static force is supplied which assumes an infinitely rigid foundation and can make the foundation design highly conservative.

In the absence of vendor supplied data, the following information may be used.

In the short circuit equation, the coefficient A, B, and C may be assumed as:

A = 10 times normal power torque
B = 5 times normal power torque
C = normal power torque

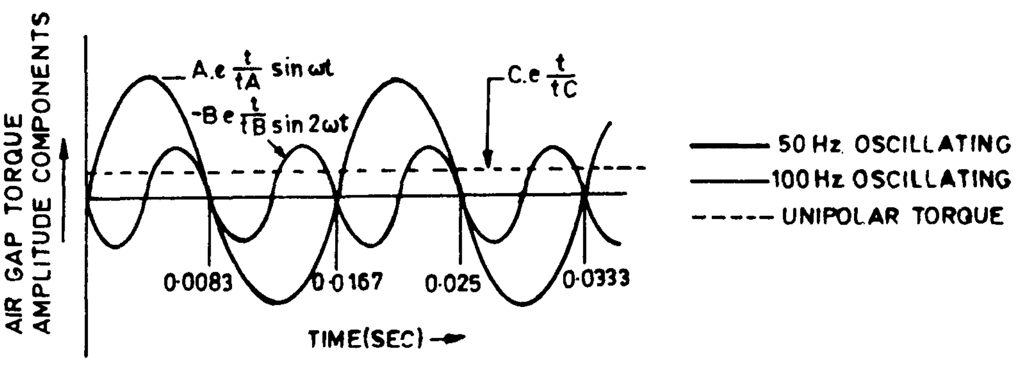

FIG. 4 SHORT-CIRCUIT MOMENT DIAGRAM

ANNEX C

(*Clause* 9.3.1)

NORMAL UNBALANCE FORCE ON TURBO-GENERATOR FOUNDATION

The unbalance forces caused by the machine during the normal operating condition are supplied by the machine manufacturer. However, in the absence of such information, the following method may be used to calculate the unbalance forces.

Turbo-generator and other similar machines are classified under the balance quality grade of G2.5. Considering one grade higher for the foundation design, that is, G6.3, the eccentricity of the rotor mass can be obtained from

$$G = e\omega$$

where

G = balance quality grade in mm/sec,

e = eccentricity of rotating mass in mm, and

ω = operating speed of the machine in rad/sec.

Example :

G = 6.3 mm/sec

ω = 3 000 rpm or 314.16 rad/sec

consequently,

e = 0.02 mm

unbalance force = $me\omega^2 \sin \omega t$

where

m = mass of the rotor

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