Civil Structures & Foundations

Special Design Considerations Applicable for Civil Structures and Foundations for Electrical Substations of Nuclear Facilities

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Typical Electrical Substation of a Nuclear Facility

ABSTRACT

Nuclear Fuel Cycle Facilities require electrical power from grid, and generally captive sub-stations are preferred to distribute and/or step down the supply to the specific requirements of the plants. Though made of structural steel, the design considerations for these structures are different from the regular industrial steel structures. Several considerations are derived from the provisions of transmission line towers, though the sub-station structures are relatively simple. This paper discusses the general and special considerations for substation structures for ready reference of practicing engineers.

KEYWORDS: Substation structures, Steel structures, Foundation

Introduction

All large industrial installations require electrical power and the nuclear fuel cycle facilities (NFCF) are no exception. The power for NFCF is tapped from nearby grids, and subsequently distributed and/or stepped down for the specific needs of the industrial plant. Generally captive substations are preferred for NFCF, a typical example depicted in Fig. 1. This would consist of one or more transformers (generally two parallel lines are preferred for redundancy), potential transformer, current transformer, along with protective items such as circuit breakers and lightning arrestors. The aforementioned electrical equipment would require structural supporting system and traditionally substation structural supports are provided with a combination of concrete and structural steel. The loads from the electrical equipment and electrical lines (wire/cables) are transferred to the supporting structures at various levels, and the support configuration has to be accordingly designed, sometimes with provisions of future expansion. These structures could include trussed towers (similar to electrical transmission towers, but smaller in height) for supporting conductors/insulators/ground wires and/or beams; trusses beams (between towers) for supporting conductors/insulators/ground wires; and other smaller trussed supports for the equipment. Thus the configurations of these steel structures differ from the conventional industrial steel structures.

Owing to the special nature of functionality, the provisions for analysis and design of substation structures are different from the regular conventional/industrial steel structures, and the design provisions for the foundations are also slightly typical for substations. Therefore, though simpler than the transmission line towers, the analysis and design of substation structures are performed in line with those of the transmission towers. The design provisions of transmission line towers are quite different from conventional industrial steel structures and therefore, entail different Indian design codes. The differences primarily occur due to the nature of load and therefore the loading calculations for substation structures are also different. There are some special provisions for the design conditions of transmission line towers which include reliability, security and safety considerations for all types of loads. Needless to mention that as a result of the differences in loading definition and design considerations, the load combinations applicable for the substation structures are different from the conventional industrial steel structures.

A brief note was presented earlier [1]. This article presents an expanded version and highlights the salient features for analysis and design of civil structures and foundations for substations. The information presented here would be useful as introduction to civil engineers involved in design and construction of substation structures and foundations.

Components of Substation Structures

The typical components of an electrical substation would include the following:

- Main Towers and Main Beams (MT / MB);
- Current Transformer structure (CT);
- Potential Transformer structure (PT);
- Lightning Arrestor structure (LA);
- Bus Post Insulator structure (BPI);
- Circuit breaker (CB);

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Fig.1: Some components of a typical electrical substation.

- Other structures such as fire wall, diesel storage tank, cable trenches, transformer oil tank & burnt oil tank (depending on the type of equipment).
- The photograph in Fig. 1 depicts some salient structures of a typical electrical substation.

Applicable Indian Codes

The substation structures are generally made of structural steel, with concrete foundations. These steel structures consist of trusses – in the form of towers or beams, grids, or simple vertical supports. However, the analysis and design of these steel structures differ from the conventional/industrial steel structures and require some special design provisions. Particularly, there are differences in the imposed loading coming on the structure (specifically the load/s from the conductors, insulators, ground wires etc.), load combinations, and design considerations. Actually, the materials and loads for substation structures would be in line with the transmission tower requirements, and would be according to IS 802 (Part 1 / Sec 1) [2]; similarly, the design provisions are provided in IS 802 (Part 1 / Sec 2) [3]; and the foundation design and construction would be according to IS 4091 [4], for which a revision is under process [5]. But of course, the substation structures, even the tower-beam systems, would be much simpler in arrangement, analysis and design as compared to the transmission towers owing to the limited plan area covered by substation(s) as well as the generally orthogonal orientation of the conductors/ground wires/etc. in the substation enclosure.

It may be hereby noted that for other general provisions for concrete, steel, and foundation design and construction those are not covered in the aforementioned codes, the appropriate Indian standards would be applicable. For example, the steel design would be governed by IS 800 [6] and the concrete design would be governed by IS 456 [7].

Statutory Requirements for Substation Structures

A significant difference in substation steel structures from conventional/industrial design would be that in addition to the aforementioned codes, there are statutory requirements to be fulfilled for sub-station structures, as enumerated in the prevalent latest version of the code [1], including the following:

- Indian Electricity Rules, 2005;
- Local and provincial byelaws;
- Fire and safety laws including IS 5613 [8];
- Civil aviation requirements/electricity rules;

Special Design Requirements for Substation Structures

The calculation of the various loads, both transverse and longitudinal, needs to fulfill three design requirements:

* ***Reliability Requirements***: There are three Reliability levels specified in the code [2], according to which the structures should be analyzed and designed.

- *Reliability level 1*: This is adopted for lines up to 400 kV class, and corresponds to a return period of loads equal to 50 years;
- *Reliability level 2*: This is adopted for lines above 400 kV class, and corresponds to a return period of loads equal to 150 years;
- *Reliability level 3*: This is adopted for special lines or for river crossing cases, and corresponds to a return period of loads equal to 500 years.

Guidelines for determination of loads and the combinations for Reliability levels 1 and 2 are stipulated in the code [2]. However, this code [2] does not cover the requirements pertaining to the analysis for *Reliability level 3*.

* ***Security Requirements***: There are two categories of Security requirements specified in the code [1] for loading and analysis of these structures.

- Security requirements under *Broken Wire conditions*;
- Security requirements under *Narrow Front Wind conditions*;

* ***Safety Requirements***: These requirements arise from the operation and maintenance loading on the structures, which might be incidental and transient in nature. The code [2]

stipulates the various loads and their points of application for different members supporting various types of wires (conductor/insulator/ground wire/etc.), for *Normal* and *Broken Wire* conditions.

Typical Loads for Substation Structures

The loads coming on the substation structures are analyzed in three major categories, according to the special design requirements discussed in the preceding section, and these are elaborated below.

* ***Gravity loads***: This is the most basic load on any structure and includes the self-weight of the tower/ beam/components of the structure along with the additional weight of the cables/wires/conductors/etc. applied at the respective nodes of the structure.

* ***Climatic loads***: The climatic loads considered for substation structures are related to the reliability requirement of the structure. The major types of climatic loads would be:

• Wind loads: The wind loads are imposed on tower beam, insulators, conductor and ground wires, etc. and are random in nature. This load is not continuous over time. The calculation of wind load for substation structures would be according to this code [2], and this is different from the national code for calculation of wind load [9]. However, it is highlighted that the cyclone factor introduced in the latest revision of the general wind load code [9] has not yet been incorporated in the code [2] for wind load on the substation (transmission line) structures. Therefore, it is recommended that the cyclone factor (k4) as incorporated in general IS code [9] must be adopted for all substation structures, as applicable according to the code [9], over and above the wind speed calculated according to the code for substations [2].

• Temperature loads: The temperatures in different localities in India are different and further, temperature in the same locality has diurnal and seasonal variations. Maximum and minimum temperatures at the specific site, including diurnal and seasonal fluctuations can be ascertained from historical records. In case such records are not available, the code [2] provides the absolute maximum and absolute minimum temperatures expected across the country, as air temperature in shade. For sites falling between two isopleths, the higher (lower) value may be adopted for absolute maximum (minimum) temperature. Average everyday temperature might be taken as 32°C across the country, except for the regions with minimum temperature less than or equal to -5°C, where the average temperature may be taken as 15°C. The radiation and heating effects of current passing through the conductors also need to be considered for calculating the maximum temperature of the conductor. In lieu of exact calculations, a maximum temperature of 85°C (95°C) may be assumed for the ACSR: aluminium conductor steel reinforced (AAAC: all aluminium alloy conductor). For the ground wire/s, the maximum temperature may be assumed as 53°C for wires exposed to sun.

• Substation structures are light structures, and therefore design is generally governed by the maximum wind pressure. Seismic event and maximum wind pressure happening concurrently is unlikely to occur and therefore not considered in design. However, in earthquake-prone areas, the substation structures should be checked for earthquake load according to the applicable IS code [10], along with zero wind and minimum temperature, as stipulated in [2].

The climatic loads would be considered for the most severe of the following conditions:

• 100 per cent design wind pressure at everyday temperature;

• 75 per cent design wind pressure at everyday temperature: generally applicable for *Security requirements*;

• 36 per cent design wind pressure at minimum temperature: could be crucial particularly for short span between towers/beams;

* ***Failure containment loads***: These are the loads related to the security requirement of the structure. The major types of *failure containment loads* would be:

• *Anti-cascading loads*: These provisions are incorporated to prevent the cascading failure of the system. For example, sequential failure of minor components such as insulators, hardware, joints–leading to failures of major components such as towers, foundations, conductors, etc. would be a cascading failure case. The structure would have to be checked for all conductors/ground wires intact on only one side of the structure.

• *Torsional / longitudinal loads*: These loads occur due to breakages of wires (conductors, ground wires, etc.) and each component should be designed for breakages of one/more of the wires connected to the structure.

• *Narrow front wind loads*: This load is applicable for suspension towers only – for a special case when higher wind velocity active over a narrow width acts on the tower and insulator/s but no wind is there on the wires. This is generally not applicable for substation structure, except for large switchyards.

* ***Construction and maintenance loads***: As the name implies, these are the postulated loads coming on the structures during operations and maintenance of the structures and this generally consist of forces, for which the magnitudes and the locations of applications have been enumerated in the code [2] for different types of members.

The loads from electrical components or their failures could be normal tension force, sag tension force, short circuit force, and broken wire force–for the different conductors, ground wires, etc. and must be provided by the electrical team for analysis. For further elaboration of the loading calculations readers are directed to the IS code [2] for general guidelines or specialist literature for special components.

Once the various loads coming on the substation structures are determined and the structure is analyzed for individual loads, the design would be performed for appropriate load combinations, and these are also elucidated in the code [2]. Broadly speaking, these are performed for fulfilling the special design requirements described above, namely, *Reliability requirements, Security requirements, Safety requirements,* and *Anti-cascading checks*. In each case, the climatic loads are specified in the load combination table (Cl. 13 [2])–whether wind pressure would be 100%, 75%, or 36%; whether wind angle would be 0°, 30°, 45°, or 90°; whether temperature would be everyday temperature, maximum temperature or minimum temperature. For each case, again, the longitudinal, transverse and vertical loading effects should be calculated for combination.

Design of Substation Structures

After the loads and the combinations are finalized, the analysis of the substation structures is performed according to the general principles of structural mechanics. Further, the general design philosophies of concrete and steel components are applicable according to the national codes [6, 7]. The design is performed for strength, serviceability, stability, and durability.

However, there exist some special provisions for design of substation (transmission line) structures as well. These include the calculation of the slenderness ratios of members that need to be performed according to the Table 6.1 / Cl. 6 [3] and the limiting values are also provided. Because of the typical nature, detailed cases are exemplified in Annex B of the code [3], which include leg member using symmetrical bracing;

Table 1: Comparison of salient design considerations for industrial steel structures and substation steel structures.

	Design consideration	Industrial steel structure	Substation steel structure
1.	Applicable wind code	IS 875 (Part 3) [9].	IS 802 (Part 1/Section 1) [2] (with cyclonic factor from [9], as applicable).
2.	Return period for wind loads	50 years (IS 875 Part 3) [9].	50 years (reliability level 1: up to 400 kV class); 150 years (reliability level 2: above 400 kV class); (IS 802, Part 1 / Section 1) [2].
3.	Wind load consideration in load combinations	100% (IS 800; IS 875 Part 3) [6, 9].	36%, 75%, OR 100% (as applicable according to load combination in IS 802 (Part 1 / Section 1) [2].
4.	Applicable seismic code	IS 1893 (Part 4) [20].	IS1893 (Part 1) [10].
5.	Applicable material properties and design code	IS 800 [6].	Material: IS 802 (Part 1/ Section 1) [2]; Design provisions: IS 802 (Part 1/Section 2) [3].
6.	Limiting width to thickness ratio for compression members	Table 2 (IS 800) [6]; Maximum value (Fe 250): 15.7 [6].	IS 802 (Part 1/Section 2) [3]; Maximum value (any steel): 25 [3].
7.	Limiting slenderness ratio	IS 800 [6]: Compression members: 180; Tension member with stress reversal (other than EL/WL): 180; Compression member only under EL/WL: 250; Tie member in truss / bracing system: 350; Axial tension only: 400.	IS 802 (Part 1/Section 2) [3]: Compression members: 150; Other members:150; Redundant members / members carrying nominal stresses: 250; Axial tension only: 400.
8.	Effective length calculation	Based on rotational and relative translational boundary conditions at the ends of the member (Clause 7.2, IS 800 [6])	Based on rotational and relative translational boundary conditions at the ends of the member, ratio of length between supports and the radius of gyration, method of loading /rigidity of joints (Clause 6.1, IS 802, Part 1 / Section 2 [3])
9.	Special loading consideration	Generally not applicable, except special structures such as nuclear, radiochemical, or hazardous facilities.	IS 802 Part 1/Section 1 [2] Broken wire condition; Anti-cascading.
10.	Design considerations	IS 800 [6] Strength; Serviceability; Stability; Durability.	IS 802 Part 1/Section 2 [3] Strength; Serviceability; Stability; Durability; Reliability; Safety; Security.
11.	Applicable foundation design code	IS 1904 [13].	IS 4091 [4, 5].
12.	Statutory requirements	Generally not applicable, except special structures such as nuclear, radiochemical, or hazardous facilities.	• Indian Electricity Rules, 2005; • Local and provincial byelaws; • Fire and safety laws including IS 5613 [8]; • Civil aviation requirements/ electricity rules.

leg member using staggered bracing; effect of end connection; bracings with and without secondary members; k-bracings with and without secondary members; among others.

For compression members of the substation steel structures, the width-to-thickness ratio limit has been specified and accordingly the allowable stresses in compression for the members must be calculated [3]. These provisions are typical to substation steel structures (transmission line structures) and dissimilar when compared to those for conventional industrial steel structures/members [6].

Design and Construction of Foundations for Substation Structures

As mentioned for the member design, foundation design and construction are governed by the national codes, unless specially provided for in this code [4, 5]. Foundation design for substation structures are performed for two conditions:

- Normal conditions;
- Broken-wire condition (all postulated combinations).

The loading information required for analysis and design of foundations are:

- Downward load: this would include the gravity loads, and downward reaction due to the climatic loads, imposed loads, etc., and construction & maintenance loads;
- Uplift load: though this is called uplift load, it is not limited to the uplift per se, but includes the lift-off caused by the upward reaction generated in one/more footing/s in the group of footings; this lift-off could occur in one/more footings to resist the high moments generated due to the action of climatic loads, imposed loads, etc., with or without construction & maintenance loads;
- Transverse load (orthogonal directions): transverse loads would be generated due to the climatic loads, imposed loads, etc., and construction & maintenance loads in both orthogonal direction in different combinations;
- Overturning moments (orthogonal directions): the moments would be generated due to the eccentric action of the resultant vertical and transverse loads on each structure for each load combination;

As required for any other foundation, foundations of substation structures must be safe against sliding, overturning, uplift, and bearing for each load combination. The safe bearing capacity of soil/rock may be estimated according to the guidelines given in the code [4, 5] or the regular Indian standard/s – but after requisite site explorations to determine the soil/rock properties at the site [11 – 13].

For foundations in soil, there are detailed guidelines [4, 5] for calculation of uplift resistance for shallow foundations. Generally, the uplift forces on the foundation would be resisted by the self-weight of the footing and the weight of a frustum of the soil in the shape of an inverted pyramid with a wedge at 30° (cohesive) and 20° (cohesion-less) with vertical, as applicable.

For foundations on rock, the uplift forces may be resisted by the rock anchors, and the following are stipulated for the same in the code [4, 5]:

- Minimum depth of embedment below footing bottom: 45 times the diameter of the anchor rod;
- Minimum spacing of rod: 22.5 times the diameter of the anchor rod;
- The diameter of the anchor rod must be determined such that the combined stresses in the anchor rods do not exceed the permissible limits;

In case of pile foundations, uplift would be resisted by the under-reamed piles. Safe loads are provided for a few salient combinations of diameters of pile/under-reams and reinforcement details in Table 2 [3, 4] for minimum pile length of 3.5 m, with increments specified for each 30 cm increase in length. These values of safe loads are applicable for sandy soil ($10 \leq N \leq 30$) and clayey soil ($4 \leq N \leq 8$). Below (above) the limit, a 25% reduction (increase) in the safe load of the pile is suggested. For other cases, reference may be made to the regular Indian standard applicable for the pile design [14 – 19].

A summary of the salient points of comparison between industrial steel structures and substation steel structures are provided in Table 1 for ready reference.

Summary

In summary, the article introduced the various components of the civil structures of electrical substations for NFCFs. The analyses of these structures are performed by the general principles of structural mechanics. However, the loads on these structures vary from the conventional industrial steel structures, along with the design considerations, design load combinations, and some design provisions as well [2, 3]. Particularly, the loads occurring due to the conductor/ground wires, and considerations of the narrow front wind load, cascading failure, broken wire conditions, short circuit forces, sag tension forces in wires make analysis of such structures typical. The design is governed by three considerations, namely, Reliability requirements, Security requirements, and Safety requirements. Foundation design is more or less similar to the conventional structures, except that the substation towers would have substantial uplift force, horizontal loads and overturning moments due to the loads coming from the conductor/ground wires, and the broken wire/ short circuit/ anti-cascading conditions. Passive resistance of soil or under-reamed piles for foundations on soil and anchor rods for foundations on rock – are recommended in the Indian codes [4, 5]. The salient features of analysis and design of the civil structures in electrical substation have been elucidated in this article with reference to the applicable Indian codes of practice. Readers may refer the cited codes and/or specialist literature for further information on the topic.

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