Some Aspects of Design and Condition Monitoring of Electric Power Transmission Towers

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Abstract: *A typical electric power transmission tower is a steel lattice structure which is used to prop overhead power lines right from the electric power generating station switchyard to electric load substations. Towers carry the heavy conductors while sustaining all kinds of natural calamities and induced disturbances. This paper expounds some crucial parameters concerning design and condition monitoring aspects of electric power transmission towers to avoid any permanent structural damage. Repairing damaged towers is a costly affair even if the cost of litigation and revenue loss due to power disruption are kept aside. A typical transmission tower condition monitoring system includes a variety of sensors to sense variations in certain critical parameters. These sensors are positioned at separate locations on the tower along with a computing device used for decision making. This paper will be helpful for researchers and electrical utilities involved in design and condition monitoring of electric power transmission towers.*

Keywords: *Design of EHV Towers, Structural Health Monitoring (SHM), Tower settlement, Earthing, Internet of Things (IoT).*

INTRODUCTION

Failure of a tower in a power corridor is normally cascading in nature which means that adjacent towers also gets affected due to some unforeseen disturbances caused in a single tower belonging to any EHV power transmission network. Proper design and condition assessment of electric power transmission tower is quite important not only because damage in an overhead tower structure can hinder reliability of the power transfer for a power system network but also due to the fact that repairing or replacement of towers is a very costly and labor intensive affair. Typical tower height varies from 15m to 55m [1]. The shape, height, and sturdiness of a tower is decided primarily on the basis of its location, power handling level, firmness of tower foundation, protection and condition assessment infrastructure available with an electrical utility. Towers design depend upon a variety of parameters and design standards depending on which an optimum design is selected e.g., clearance of the lowest conductor from the ground, clearance from buildings of low and medium voltage lines are clearly stated in The Indian Electricity Rule, 1956 [2]. Apart from these rules and design standards selected for tower construction, a designer has to consider other rules and regulations too e.g., placement of warning lights on high towers so that aircrafts maintain a safe distance from them is a recommendation of The International Civil Aviation Organization [3].

Condition based monitoring of a tower is of prime importance as towers cost about 35% to 45% of the material cost of the line, are difficult to install and repair, and can impact the reliability of a power system network [4]. Proper condition monitoring of an electrical tower primarily involves structural health monitoring but it also includes leakage current monitoring, effects of wind, icing, tower settlement etc. Several condition monitoring techniques i.e. Structural health monitoring, Transmission tower settlement, tower footing earth resistance monitoring, icing and wind monitoring and an overview of modern tools and nascent technologies used for transmission tower condition assessment is also covered in the present paper.

DESIGN OF EHV TOWERS

For ensuring reliable operation of Electrical Power Transmission Network, it is formidable task for utility engineers to develop a flawless strategy for implementing effective condition monitoring techniques suitable for the given power corridor towers installed at specified locations. Four-legged lattice towers are commonly used as electric power transmission towers in EHV systems [5]. The Power Grid Corporation of India Limited (PGCIL) - key organization entrusted within Indian Power Sector framework for implementing and performing all kind of assignments related with design, installation, operation and smooth evacuation of electric power through EHV Transmission Systems network, has prescribed following design procedure for optimum tower design [6]:

- *Selection of Clearances*

Transmission lines have to follow strict guidelines for height clearances over streets, sidewalks, alleys, driveways, and other traffic areas. Clearance is needed all along the transmission line in order to limit the exposure of the general public and nearby conductors to the electric field of a particular conductor in the transmission line. Clearances are sub-divided into ground clearance and horizontal clearance (which determines horizontal distance of line conductors from any structure) [4].

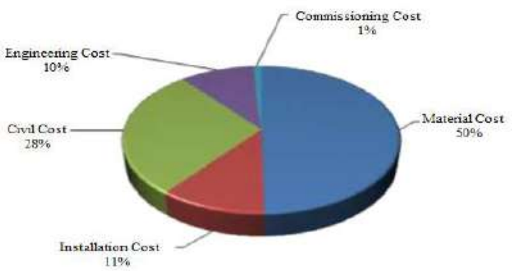
Reference values for ground clearances are provided to check if the calculated height of the tower is within permissible limits. The factors which govern the calculation of height of a tower are: Minimum allowable clearance from ground (h_1), Maximum allowable sag (h_2), Vertical spacing between the conductors of the line (h_3), Vertical clearance between ground wire and top conductor (h_4) [4]. Thus, the total height (h) of tower is given by:

$$h = h_1 + h_2 + h_3 + h_4.$$

Horizontal Clearances are provided to keep a safe distance of line conductors from any structure in its vicinity. Shielding wires are provided on the top of the tower for protection against lightning strokes. These wires provide a shield angle of 20 to 30 degrees with the vertical [4]. The permissible values for ground clearances and horizontal clearances are as shown in Table I.

Table I. *Permissible values for Ground and Horizontal Clearance [4]*

Ground Clearance	
Transmission Voltage	**Permissible minimum Clearance in (mm)**
66 kV	5490
132 kV	6100
220 kV	7016
400 kV	8840
Horizontal Clearance	
Up to 11 kV	1219
11 to 33 kV	1829
Above 33 kV	1829**



** Increase horizontal clearance by 305 mm with every additional 33 kV or part thereof.

- *Insulator String Design*

In EHV and UHV AC lines, insulator string design is primarily decided as per the desired performance under switching over voltages whereas in HVDC lines, the deciding factor is pollution severity [7]. Also, for optimum insulator string design, the dynamic wind load factors are determined under different reliability conditions for swing angle of suspension insulator string [8].

- *Bundle Conductor Design*

Bundled conductors are mainly used in EHV lines to minimize the corona discharges by reducing the voltage gradient around the line. Design of bundled conductors depends upon selection of spacers which are used for grouping conductors of the same phase and prevent them from touching each other [9].

- *Tower Configuration Analysis*

Tower configuration depends primarily on the horizontal and vertical spacing between conductors, line angles and the number of circuits. The transmission structures are sub-divided into:

- *Lattice Steel Towers (LST)*: LSTs have a steel framework which can carry either a single or double circuit line. The double circuit line towers are generally higher than single circuit line towers as the conductors in them are stacked in a vertical configuration [10].

- *Tubular Steel Poles (TSP)*: TSPs are hollow steel poles.

Once a generalized configuration of tower structure is decided, a matrix based structural analysis is performed in order to ensure that the tower configuration meets the equilibrium and compatibility requirements [4]. Lastly, the bracing system for given tower configuration is selected as per force analysis for external loads. These external loads are affected by wind speed. The bracing systems are primarily of five types, namely, Single web, Double web or Warren, Pratt, Portal, Offset or Staggered [11].

- *Tower Weight Estimation*

Tower weight estimation is critical for foundation design. A maximum deviation of ±3% is permissible on transmission line tower weights of 132 kV and 220 kV. For 400 kV transmission line tower, the maximum permissible deviation in weight is ±5%. Similarly, the permissible maximum deviations for conductor parameters like conductor weight, tension and resistance are ±10%, ±8% and ±5% respectively [12].

Once the tower configuration is selected and the conductors it is going to bear are decided, the weight of the tower can be estimated. After tower weight estimation, the foundation is designed using methods like The Hansen's method [13].

- *Analysis of cost of the Line*

The total cost of a transmission line can be subdivided into Material Cost, Civil Cost, Installation Cost, Engineering Cost and Commissioning Cost. Typical values for the contribution of these costs can be classified as shown in Figure 1.

- *Economic Evaluation of Line*

After designing the line by following the aforementioned steps, economic evaluation of line is performed to ensure the design is economically feasible or not using mathematical models. Thus, it can be concluded that depending upon wind speed, terrain category, reliability level and several other factors an optimal design of tower is decided [6] [12]. The various Terrain categories along with average height of surrounding objects are mentioned in Table II.

Table II. Terrain Categories [6] [12]

Terrain Category	Average height of surrounding objects	Description
1	1.50 m	Exposed open terrain with few or no obstructions.
2	1.50 m to 10 m	Open terrain with scattered obstructions.
3	>10 m	Terrain with numerous closely spaced obstructions.

Reliability levels are an indicator of the sturdiness of the tower. Reliability level 1 is adopted for EHV transmission lines up to 400 kV class, reliability level 2 is adopted for EHV transmission lines above 400 kV class. Reliability level 3 is selected in special cases like near river crossings. Valuable work of various researchers which provides in depth information on tower design are included in [15-28]. The chemical, mechanical and metallurgical properties of the various materials used in the tower are specified in several standards. If a tower is designed for installation in India, it must follow the Indian Standards. Some of the Indian standards which govern the design of towers are as mentioned in Table III.

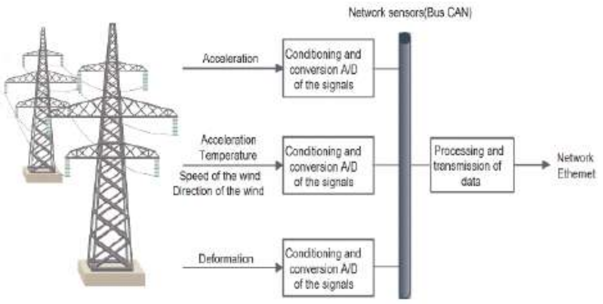


Table III. Indian Standards on Tower Design [3] [59]

Parameter	IS Standard
Code of practice for use of structural steel in overhead transmission line towers: Materials and loads permissible stresses	IS 802-1 (Section1,2)
Dimensions for hot rolled steel beams, column channels and Angle sections	IS 808
Technical supply conditions for threaded steel fasteners	IS 1367
Bolts	IS: 6639, 3757
Nuts	IS: 6623
Heavy Washers	IS: 6610
Plain and Lock washer	IS: 5639
Hot-deep zinc coatings on structural steel	IS: 4759
Tolerance for fabrication of steel structure	IS: 7215
Fastener	IS: 10238, 12427
Danger Notice plate	IS: 2551
Criteria for earth quake design of structure	IS: 1893
General Construction in steel- code of practice	IS: 800

Thus, it is inferred that design plays vital role in structural integrity of any EHV power transmission tower network.

CONDITION MONITORING TECHNIQUES

Monitoring of transmission lines via traditional means is labor intensive and cumbersome task. Condition monitoring and predictive maintenance techniques decides the reliability and availability of the transmission line for smooth evacuation of electric power from one point to other. The major condition monitoring techniques used in towers are covered in this section.

- *Structural Health Monitoring (SHM)*

The aim of SHM is to monitor deformation in the electric power transmission tower structure. This deformation can be due to degraded structural connections and bearing wear or it can be a fatigue crack [29].Tower legs are made of steel and set in concrete. Cracks and fissures in the concrete allow penetration of water, oxygen, and salts into concrete leading to corrosion and weakening of the legs of the tower. This eventually leads to deformation of tower structure over a period of time [36-37]. This aspect of tower degradation is monitored by SHM techniques. The various sensors with their respective purpose, positioning on the tower and respective sampling per second (SPS) rates are given in Table V.

Table V. *Different Sensors for Structural Health Monitoring [33-35]*

Monitoring Sensor	Role of Sensor	SPS	Location of Sensor
Acceleration (Wilcoxon) Sensor	Detect possible rotations of the tower.	20	Two at central part, Three at Top part.
Deformation sensor	Detect structure deformations by sensing change in resistance (R). R enhance then Compression & R decreases then Dilatation.	20	Four sensor at bottom base of the tower.
Temperature sensor	Detect temperature of tower. Range from -55⁰C to +150⁰C`.	1	One Sensor
Wind speed (Anemo-meter) sensor	Monitor wind speed & direction. It's direction presented by potentiometer & Sensor R varies by reed position.	1	One Sensor at top of the tower.

Sensors used for SHM are connected to a central module. This module contains a signal conditioning circuit, analog to digital (A/D) converter and a microcontroller. A Controlled Area Network (CAN) protocol is adopted by this system to interconnect multiple modules and fuse together the information from these modules. The erudition provided is then steered to a computer. This computer receives and stores the information by employing a socket interface [33-37]. A regular layout of an SHM system is as shown in Figure 2.

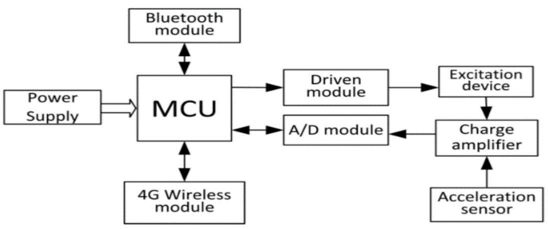
- *Tower Settlement Monitoring*

The terrain contingencies of transmission tower are quite complex and may lead to displacement, inclination, cracking and subsidence of the tower. A deviation in foundation settlement endangers the safety of transmission lines as it impacts the sag and stress considerably. This variation in sag and stress leads to distortions in the tower leg which influences the capacity of towers to withstand sustained wind and icing effects. Thus, it is necessary to strengthen the online monitoring of tower inclination to ensure the safety of transmission lines [38-39].

Researchers have tried to solve this problem of variations in the stress of the tower during settlement by using computer-based simulations and force analysis techniques. Some researchers proposed an analysis of the vibrational characteristics of the tower. SHM techniques can only discursively reveal the state parameters of stress when deformations in the tower structure are extensive. Stealth faults like minute deformations in tower structure can't be detected easily. Thus, SHM can't determine the impact of changes in Tower settlement. Among the proposed solutions, the vibration-based monitoring system is more preferred for monitoring deviations in transmission tower settlement [38-40]. The various elements of this system can be sub-divided into the following units: excitation device, acceleration sensor, condition monitoring device (CMD), power supply and a monitoring station [38-40]. The function of these units is given in Table VI and a typical layout is shown in Figure 3.

Table VI *Units of vibration-based tower settlement monitoring system [38]*

Name of the Unit	Function
Excitation Device	Generates Impulse excitation.
Acceleration Sensor	Detect possible deformations.
CMD	Generates Fourier transform of signal to obtain frequency domain response.
Monitoring Station	Receives data from multiple CMDs.
Power Supply	Provide electrical power to the settlement monitoring system.



- *Leakage Current Monitoring*

Ground faults on transmission lines occur frequently due to which a high potential is acquired by towers in the vicinity of the fault. If this tower voltage is above a threshold, it can be hazardous for humans or animals in its proximity. Traditionally, the number of accidents due to such potentials has been very low but nowadays, transmission line right of way is getting narrower due to densely populated areas due to which, the probability of the presence of humans or animals in the proximity of the towers at any time has risen. As a result, designers have expressed concern about the increase in the probability of accidents at towers [41].

Moreover, during a lightning strike, a very current with a large magnitude and a fast rise time start flowing which induces high voltages in the tower. This may eventually lead to insulation failure [41]. Thus, high voltage power transmission systems require lightning protection and insulation coordination schemes. Earthing of each tower of an electrical transmission line is done and footing resistance of each tower is measured in dry season before stringing the earth wire. Footing resistance of the tower should never exceed 10 ohms. Higher the footing resistance, higher the chances of failure due to lightning strikes. Generally, the leg which is specifically marked for providing earthing members is marked with capital letter A. Earthing is provided at only one of the legs of a tower but in case of river crossing and railway crossing towers earthing is provided at diagonally opposite two legs of a tower. Either pipe or counterpoise earthing is used for **earthing of the electrical towers [42].** In case of **pipe earthing system,** a galvanized steel pipe (diameter 26 mm and length 3m) is buried vertically in soil such that the top of the pipe is 1m below the ground level. Surroundings of the pipe are packed with layers of charcoal and salt which are alternating in nature. This ensures that the surroundings of the pipe remain moist and the footing resistance remains within prescribed limits. In case of Counterpoise earthing, galvanized wire (10.97 mm diameter, 25 m minimum length) is used. The galvanized wire is connected with the leg of the tower by a galvanized lug. The wire is buried tangentially under the ground of minimum 1m depth [42].

Leakage current monitoring is used for condition monitoring of earthing of the tower [43]. Information from voltage and leakage current sensors placed on the tower are sent using a communication module to a control station where the information is analyzed and the necessary actions are taken accordingly. Leakage current coupled with signal processing techniques is a strong diagnostic tool for presenting useful information on the status of degradation of the surge arrester [41-44]. A simple block diagram for leakage current monitoring is as shown in figure 4.

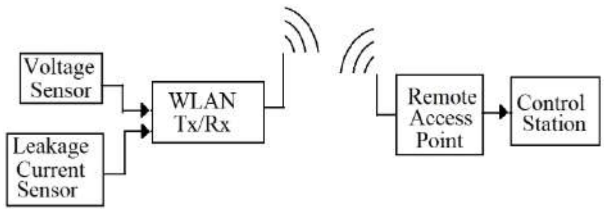


Figure 4. Leakage Current Monitoring [44]

- *Icing Monitoring*

Transmission line icing often leads to accidents like unwanted tripping operations, breaking of conductors, conductor galloping, insulator string flashover, etc. Ice accretions which are commonly observed on transmission lines can be subdivided into: Glaze, Hard Rime, Soft Rime, Hoar Frost, and Snow and Sleet. Among these ice accretions, glaze is the most dangerous one for transmission lines. Meteorological conditions, terrain and geographic conditions significantly influence the ice accumulation speed and the amount of ice deposited [47]. The system used to effectively monitor the icing on transmission line must take the icing information and by real-time monitoring of the temperature and other parameters the amount of ice coating is determined [45-47]. A typical icing monitoring unit consists of Tension sensor, Deflection angle sensor, temperature and humidity sensor, wind speed direction sensor, Atmospheric pressure sensor, Rainfall sensor, Sunshine intensity sensors, Image processing unit [48].

These sensors collect the necessary information and help in determining condition of Icing in a region so that proper de-icing action can be done. Thickness, density, and type of icing can be obtained by using a combination of these sensors and image processing techniques. Icing information of three or more than three base towers is generally needed to develop the mechanical model of computing icing coating and calculating the icing thickness accurately in order to determine icing density and icing type with the image processing technology [45-48].

- *Wind Monitoring*

A Transmission towers installed in coastal areas is prone to damage by hurricanes or high speed seasonal winds. Critical damages to the tower structure due to winds can be detected using SHM in offshore areas but in coastal areas in order to enhance reliability, dedicated wind monitoring systems are employed. Also, monitoring of wind-induced vibrations is of prime importance for power system security [49-55].

A variety of solutions have been proposed for monitoring of the effects of wind but nowadays Optical fiber-based sensing system are gaining attention. Since these systems have relatively lower cost and due to its packaged structure, it can prove to be a safe, robust, and reliable monitoring system. Specifically, tilted fiber Bragg grating (TFBG) based sensors which are a nascent species in the family of optical fiber based sensor is employed for this purpose. It works on Bragg grating technology and it allows single-point sensing with very controllable cross-sensitivities, absolute and relative measurements of various parameters [49-55].

RECENT DEVELOPMENTS IN CONDITION MONITORING OF TOWERS

- *Neural Network based monitoring techniques for Transmission Tower Structure*

Diagnosis and assessment procedure of structural damage of transmission tower primarily uses mathematical models to find its dynamic indicators. If tower is damaged, some mathematical characteristics of the structure will change. To analyze this change and ensure proper decision making, neural network appraisal method of tower structure is used. In this method, warning processing step of tower structure damage is given based on neural network analysis method which allows effective appraisal of tower structure damage. Generally, nonlinear relationship between displacement, velocity and the structural dynamic response of transmission tower is established. This relationship is used for assessment of structural damage [56].

- *A Wireless Multifunctional Monitoring System of Tower Body Running State Based on MEMS Acceleration Sensor*

Micro-Electromechanical Systems (MEMS) have miniaturized mechanical and electromechanical elements which are fabricated using micro-fabrication technology. With the development of MEMS technology, MEMS-based acceleration sensors are used for health monitoring of a tower structure. In this method, tilt is calculated based on the difference between the acceleration due to combination of gravity and other stresses and the acceleration due to gravity alone. A wireless system which uses wireless sensor nodes, transmits the tower running state data to the monitoring server [57].

- *Transmission Tower Vibration Analysis System Based on Internet of Things (IoT)*

IoT is a system of intertwined computing devices working in unison with mechanical and digital machines. It has the capability to convey data over a network without demanding a man-to-man or man-to-machine interaction. IoT based vibrational analysis system for transmission tower consists of three major units: a network of sensing unit, data communication unit and software unit. The sensing network consists of multiple vibration acceleration transducers which use WIFI technology for data communication. The Software unit governs the accommodation, interpretation, and processing of identified data [58].

CONCLUSION

Electric power transmission towers are the primary supporting units of overhead transmission lines. Design, construction and installation of electric power transmission towers have proceeded rapidly over the years with the objective of reducing construction time as well as clearance requirements. The design procedure of electric power transmission tower is covered in the paper. These electric towers are prone to failures as they sustain all kinds of natural calamities and induced disturbances. For mitigation of these failures, towers are needed to be regularly monitored. Traditionally used condition monitoring techniques like SHM, Tower settlement monitoring, etc. are also covered in this paper. Finally, the nascent technologies involved in the condition assessment of electric tower are discussed.

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