Review

Sources of vibration and their treatment in hydro power stations-A review

Rati Kanta Mohanta a,b, Thanga Raj Chellia a, Srikanth Allamsetty c,a, Aparna Akula d, Ripul Ghosh d

a Hydro-Electric Systems Group, Dept. of Water Resources Development and Management, Indian Institute of Technology Roorkee, India
b Odisha Hydro Power Corporation Ltd., India
c School of Electrical Sciences, Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
d Central Scientific Instruments Organization (CSIR-CSIO), Chandigarh, India

A B S T R A C T

Vibration condition monitoring (VCM) enhances the performance of Hydro Generating Equipment (HGE) by minimizing the damage and break down chances, so that equipment stay available for a longer time. The execution of VCM and diagnosing the system of an HPS includes theoretical and experimental exploitation. Various studies have made their contribution to find out the vibration failure mechanism and incipient failures in HPS. This paper gives a review on VCM of electrical and mechanical equipment used in the HPS along with a brief explanation of vibration related faults considering past literature of around 30 years. Causes of the vibrations on rotating and non-rotating equipment of HPS have been discussed along with the standards for vibration measurements. Future prospectus of VCM is also discussed.

Keywords:
Vibration condition monitoring
Vibration monitoring
Health conditioning
Health monitoring
Hydro power plants
Electrical and mechanical equipment

Contents

1. Introduction ....................................................................................................... 0
2. Sources of vibration .......................................................................................... 0
  2.1. Reasons for vibrations on rotating equipment ............................................. 0
  2.2. Reasons for vibrations on non-rotating equipment ....................................... 0
3. Vibration on rotating hydro generating equipment ......................................... 0
  3.1. Motors ......................................................................................................... 0
  3.2. Turbines .................................................................................................... 0
    3.2.1. Defective bearings ............................................................................... 0
    3.2.2. Improper lubrication ........................................................................... 0
    3.2.3. Imbalance ............................................................................................. 0
    3.2.4. Eccentricity ......................................................................................... 0
    3.2.5. Soft-foot ................................................................................................ 0
    3.2.6. Misalignment ....................................................................................... 0
    3.2.7. Rough zone operation ......................................................................... 0
    3.2.8. Abrasive erosion .................................................................................. 0
  3.3. Rotor .......................................................................................................... 0
4. Vibration on non-rotating hydro generating equipment ................................... 0
  4.1. Transformer ................................................................................................ 0
  4.2. Penstock ..................................................................................................... 0
  4.3. Draft tube vibration .................................................................................... 0

* Corresponding author.
E-mail address: askanth31@gmail.com (S. Allamsetty).
Peer review under responsibility of Karabuk University.

http://dx.doi.org/10.1016/j.jestch.2016.11.004
2215-0986/© 2016 Karabuk University. Publishing services by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Please cite this article in press as: R.K. Mohanta et al., Sources of vibration and their treatment in hydro power stations-A review, Eng. Sci. Tech., Int. J. (2016), http://dx.doi.org/10.1016/j.jestch.2016.11.004
1. Introduction

Vibration of equipment has been a severe problem in Hydro Power Stations (HPS) from the very beginning of power generation. Failure of the equipment due to vibration causes shut down, or sometimes, even a disaster in hydro power station (HPS) [1,2]. VCM has to be done to examine the performance of such equipment online automatically and to know the status of complex systems in hydropower generation. In HPS, online vibration monitoring is provided in various parts of hydrogenating equipment including relative shaft vibration, bearings absolute vibration, turbine cover vibration, thrust bearing axial vibration, stator core vibrations, stator bar vibrations, stator end winding vibrations. Non-contact capacitive proximity probes are usually provided to dynamically monitor the motion of the generator/turbine shaft relative to the bearings. The probes need to be insensitive to electrical run-out, magnetic field and shaft mechanical surface imperfections. Low-frequency accelerometers is usually provided to monitor the absolute vibration of the bearings and of the turbine cover. A multi-channel, multi-tasking, online programmable digital processing unit is provided for system configuration for processing vibration data from vibration probes. Going for VCM is very important as it provides early indication of impending failure. By doing this, any technical person can easily detect the fault or abnormal condition before it causes tripping of the unit. Thus, unnecessary maintenance can be avoided and the resources can be saved. This paper discusses various sources of vibrations and the methods for their treatment. There are a significant number of previous studies on this topic, but there is a need for a review of all those studies to understand the vibration related issues in a better way. This paper presents the information from various existing literatures to give a brief knowledge about the VCM.

The condition of a machine can be estimated by measuring the vibration levels. Fault detection techniques and vibration signal processing are the other techniques which have more scope to study. The HGE vibrate with the influence of different factors i.e. electrical, mechanical and hydraulic factors [3]. The causes for these vibrations are very complicated and mostly unavoidable. Inspection of these causes and handling them at an earlier stage are the necessary steps to be taken for safe and stable operation. Vibrations are most dangerous stresses of an HPS, which occur during the sudden opening or closing of wicket gates. Analysis of vibration transients of an existing HPS prevents harmful resonances those occurred at a plant and hence reliability/availability of the equipment is increased. The VCM can be inferred in a least time and gives details regarding the incipient failure. This paper provides a comprehensive review on the said topic with the support of experimental studies. The distribution of publication of research articles covered in this review is shown in Fig. 1. However, there are also a number of standards, professional bodies/group related to this area, i.e. IEEE Guide for the rehabilitation of hydro-electric power plants, International Energy Agency (IEA), IEEE Standard 492-1999, Task Committee ASCE, BIS Standard IS-12800 (Parts I, II, III), 1991 etc., and their contributions are absolutely significant in the condition monitoring area of HPSs.

Different sources of imbalance, bearing problems, wicket gate problems and shear pin failure can be determined by monitoring of vibration at turbine guide bearings and the generator. VCM is the most effective technique to find machine faults [4,5] by selecting input and output with data acquisition and signal processing. High frequency phenomena can be monitored using data acquisition and sensors which are attached to the required equipment [6]. Excess vibrations cause wear & tear along with fatigue failure of guide vanes, runner blades, rim, bearing, shaft seal, shaft, runner labyrinth, Loose or shear nuts, wedges, stampings, bolts, pole wedges etc. at affected locations. These rapid wear & tear and fatigue failure need frequent replacement of equipment [7]. Excess vibrations can also cause excess noise.VCM provides root causes of fault sequence [8] in failure mode. Finite element analysis plays a significant role on vibration studies [9,10].

2. Sources of vibration

Different components of HPS have been shown in Fig. 2. Here turbine, generator, and power transformer are cost intensive and most important electro-mechanical equipment [11]. The rotating elements generate specific vibration frequencies. Quality and
performance of a Machine or equipment are defined by vibration amplitude. As this vibration amplitude increases the rotational elements cause more severe problems [12].

The main sources of vibration [7] have been given below.

- Electrical vibrations,
- Mechanical vibrations,
- Hydraulic vibrations.

Vibrations occur not only on rotating equipment, but also on non-rotating equipment. Reasons for the vibrations on various equipment have been listed below.

2.1. Reasons for vibrations on rotating equipment

- Turbine runner: Vibrations on turbine runner may be due to any of the following reasons. Those are mechanical imbalance, hydraulic imbalance, misalignment, cavitations, turbine bearing instability (due to rubs & hydraulic forces), rough zone operation, improper lubrication of mechanical parts, defective bearings [13], breakage of wicket gate linkage, cracked or chipped blades and shaft.
- Rotor: Vibrations on the rotor may also be due to the same reasons those mentioned for the runner along with another reason i.e. rotor rubs [14].

2.2. Reasons for vibrations on non-rotating equipment

- Draft tube: Cavitations, Power Swings and Draft Tube Resonance.
- Seal erosion: Depends on water quality.
- Penstock resonance: Cavitations
- Generator: Electromagnetic force
- Transformer: Magneto motive forces

The main source of vibration in both turbine and generator are (1) Abrasive erosion, (2) Recirculation, (3) Mechanical looseness [11–15]. Vibration occurs mostly in transformers, electric motors, turbine and generators, and measuring this vibration signal using advanced tools helps to diagnose the faults those occur in such equipment.

3. Vibration on rotating hydro generating equipment

Reasons for vibration on rotating hydro generating equipment such as motors, turbines and rotors of the generators have been illustrated in detail in this section as follows.

3.1. Motors

The vibration of motor is classified as Mechanical, Aerodynamic and Electromagnetic. Mechanical problems are due to

- Imbalance
- Misalignments
- Winding damage due to mechanical shock,
- Defective bearings,
- Looseness, and
- Soft-foot, impact or fretting etc.

Aerodynamic problems are due to

- Discrete blade passing frequencies,
- Resonant volume excitations with in motor,
- Ventilation fans and
- Broadband turbulence etc.

Vibrations related to electrical faults are due to imbalanced electromagnetic forces on the rotor and stator. This imbalance is due to air gap eccentricity, broken rotor bars, unequal distribution of air gap flux, inter-turn faults, shorted or open stator and rotor windings, unequal phase currents, magnetostriction and oscillations of torque [16]. The relation between electrical supply frequency and rotational frequency [7] can be expressed mathematically as shown in equation (1).

\[ f_e = \frac{f_s \times P}{2} \]  

where \( f_e \) is electrical supply frequency,  
\( f_s \) is shaft rotational frequency,  
\( P \) is number of magnetic poles.

3.2. Turbines

Vibrations of hydraulic turbine are due to extreme force fluctuations caused by cavitations. VCM can be carried out to find the frequency at which resonance occurs in foundation and turbine-supporting structure. Pressure difference by large cavities causes hydrodynamic pulsations and cavitation-induced vibration in hydro turbines [17]. The main reason for turbine erosive wear is cavitations only. The Damage of a Francis hydro turbine due to cavitations has been shown in Fig. 3.

Instead of changing the natural frequencies, hydraulic excitation force is required to be avoided to minimize resonant vibra-
3.2.1. Defective bearings

This is due to normal erosion during use. Machine speed influences the process of finding bearing faults using vibration signals when bearing condition is progressively worse [21]. When failure is approaching, vibration may decrease [2].

3.2.2. Improper lubrication

Improper lubrication of mechanical parts with unsuitable parameters of the lubrication system causes turbulence of oil film and results in destruction [15].

3.2.3. Imbalance

Debilitation of different components of the rotating assembly causes imbalance. The vibration due to imbalance is radial and increases with rotational frequency [13,15]. During vibration condition analysis if any imbalance condition is diagnosed, the machine must be brought back to balanced condition as soon as possible without going for cost consideration. Imbalance occurs when rotor weight is unequally distributed about its rotating centerline. This imbalance may be due to any of the following reasons. Those are eccentricity, distortion, imperfection casting, corrosion, wear, addition of keys and keyways, clearance tolerances and deposit build-up.

3.2.4. Eccentricity

It is the situation of fluctuating air gap between rotor and stator [2, 22–24]. This causes electromagnetic imbalance and alternating stresses on stator and results in stator degradation, shorts, insulation breakdown and loosening iron [5]. When this eccentricity is high, imbalanced magnetic pulling takes place which causes the surface of stator rubbing against that of the rotor. Air gap eccentricities are of two types. Those are dynamic air gap eccentricity and static air gap eccentricity.

In static air gap eccentricity, the radial air gap is fixed in clearance, i.e. it has a fixed length. The static eccentricity is an outcome of wrong installation of the stator or the rotor or ovality of the stator core. A maximum of 10% air-gap eccentricity is permissible [2]. When the air gap of generators varies 10–15% of its minimum length, a significant imbalance occurs after 15–20 years, which may reach up to twice the value of that of a new one. If the stator frame and core assembly are imbalanced under this condition significant vibrations would take place. In this condition, within 2–3 years, if a remedial measure has not been taken, stator-winding fault will occur due to mechanical abrasion of stator insulation [25]. This eccentricity must be lower to reduce vibration and to prevent the imbalanced magnetic pull. Further, unbalanced mass on rotor causes dynamic eccentricity. In some cases, dynamic displacement of shaft in bearing housing also causes this eccentricity [8]. Practically, both dynamic and static eccentricities are co-existing. Static eccentricity exists in new machines due to assembly and manufacturing [2,26]. The faults related to eccentricity are monitored using vibration signal. High-frequency vibration elements for both dynamic and static eccentricities were described in [24]. Vibration of the stator with low frequency in mixed eccentricity was explained in [2] and mentioned here in Eq. (2).

\[ F_v = 2f_s \pm f_r \]   
where \( f \) is fundamental supply frequency, \( F_v \) is vibration frequency and \( F_r \) is rotor frequency.

Modified Winding Function Approach (MWFA) method for modeling of eccentricity was explained in [27,28]. The basic Winding function approach gives incorrect results due to unequal mutual inductances [29]. There were some other approaches described in literature to detect eccentricity faults [30–32]. Eccentric faults can be found out from torque data [33]. Both magnetic equivalent circuit and Winding function approach are used to compute inductances for eccentric induction machine [34]. Effects of horizontal and vertical misalignment and load imbalance of induction machine were described in [2,35].

3.2.5. Soft-foot

This case indicates that the machine feet are not coplanar with base or shims are not installed properly. This soft foot condition leads to excessive vibration, dynamic stress and distortion. Due to the combination of electromagnetic and mechanical stresses, electrical faults and break down in stator take place. Low support stiffness and resonance by improper foundation design results in high vibrations. A good foundation is necessary to minimize the vibrations [5]. The soft foot problem is common in industrial applications, which causes deterioration of structures, components and machines. During this state, motor consumes more electrical power due to which machine degrades.

3.2.6. Misalignment

The picture, in which workers trying to detect the misalignment has been shown in Fig. 4(a). Misalignment from the line of shafts causes vibration in radial as well as in axial directions. These vibrations increase with rotational frequency of lower order harmonics.
It also leads to bearing failure and overheating.\textsuperscript{36} The shaft misalignment can be either angular or offset. If it is angular, the angle between the machine moved and the shaft center line of a stationary machine is different in vertical and horizontal planes. This angle is zero degrees for any stationary machine as explained in \textsuperscript{5}. Breakage of wicket gate linkage due to misalignment has been shown in Fig. 4(b).

3.2.7. Rough zone operation
Severe vibrations cause surging in the hydroelectric turbine generator. When the surging frequency tallies with the natural frequency destructive resonance takes place along with huge power swings and unmanageable penstock pressure surges. To meet the wide ranges of power system, sometimes hydropower units are being operated in the draft tube surging region. Draft tube vibrations also occur during remote operations of a unit having operator in a surging region. During this operation, the operator in the power plant can feel or hear some noise and accordingly he can take appropriate steps to get out of this rough zone.\textsuperscript{39}

3.2.8. Abrasive erosion
It is the mechanical elimination of metal particles by the action of suspended solids rather than liquids or fluids in the water. Runner blade surfaces and leading edge get worn due to the presence of sand or silt in water.\textsuperscript{11}

3.3. Rotor
Inter turn faults in a hydro generator rotor winding lead to rotor earth faults, local overheating and imbalanced pull. All together, results in rotor vibration as mentioned in \textsuperscript{40,41}. On-line detection of these faults first described in 1971\textsuperscript{16,42}. When insulation of rotor poles fails, the unequal current in windings creates non-uniform magnetic field and thus the vibrations increase. Current flowing in all the three phases should be equal and the maximum difference in phase currents is limited to 20\%\textsuperscript{7}. Vibrations frequency characteristic of rotor during normal operation of generators and 10\% inter-turn faults in the rotor winding has been shown in Fig. 5. When a fault occurs, the rotor vibration increases with frequency. Due to rotor winding inter-turn fault, the air-gap distorts cause imbalanced magnetic pull on the rotor. This causes pulsating magnetic pull on the stator that ultimately results in stator vibrating.\textsuperscript{43} In \textsuperscript{44,45} authors concluded that the rotor vibration in an HPS cannot be determined whether it is a partial jam or an imbalance, from the profile of vibration signal.

4. Vibration on non-rotating hydro generating equipment

4.1. Transformer
Magneto motive force causes vibrations in core and windings. These vibrations are associated with a noise, i.e. humming which has a frequency twice the supply frequency. The performance of the transformer goes down as these vibrations increase. This vibration cannot be eliminated completely, but it can be reduced to some extent using vibration pads and proper fixing of inside components of the transformer.

4.2. Penstock
Penstock is a pressurized conduit through which the water can be transferred from the reservoir to the turbine. Penstock can be

---

\textbf{Fig. 4.} Turbines (a) Misalignment detection\textsuperscript{37} and (b) Breakage of wicket gate linkage\textsuperscript{38}.

\textbf{Fig. 5.} Vibration Frequency Spectrum Characteristic of Rotor (a) before and (b) after fault.\textsuperscript{43}
Draft tube vibration is the most interesting phenomenon which causes great obstruction to operation of Francis turbine. This is due to flow instability associated with overload or part load operation of the turbine. Swirling flow causes a vortex inside the draft tube. Draft tube surges cause vibrations, noise, penstock pressure surges and power swings as well [39]. Cavitation can affect efficiency and can also cause eroding of metal, damage of the turbine or forced shut down of the machine. Cavitation can be detected by measuring the vibration of the turbine and draft tube with the help of fil-

tering the signal and accelerometer. Operation of the unit should be avoided in this damaging region [4]. The details of vortex rope in the draft tube by jet control method during part load operation of Francis turbine were described in [56]. Advantages of vortex rope jet control method have been given below.

- No additional devices required to install inside draft tube.
- Any runner modifications are not required.
- It can be adjusted according to the operating point and can be switched off when it is not required.
- It is robust and simple.
- During jet operation, the overall efficiency of turbine does not change.

Harvey [57] was the first one who started observing the helical vortices in a straight diffusing pipe with air-controlled move in twisting flow. Benjamin [58,59] performed an analysis on the swirling flow after the breakdown of the vortex. Cassidy and Falvey [60] discussed the dependency of vortex break down on the ratio of angular momentum and axial momentum [61].

When local pressure falls below the vapor pressure of water, water column separation takes place either in transient or steady conditions. Due to this water column separation the turbine and the other hydraulic components get damaged with cracks in internal linings [50]. By preventing these separated columns of water in draft tube, large vortex can be minimized to some extent. Helical flow causes unequal forces in the draft tube cone. Minimum and maximum pressures those occur at the center of vortex core and on the wall have been shown in Fig. 6(a) & (b) respectively. The unstable vortex core is due to swirl by turbine blades [50,61]. Problems due to draft tube vibrations are reviewed in detail in [63].

Cavitation presents itself in an informal pitch against the metallic, outer side of turbine parts due to the formation of cavities [64]. Formation of vapor or bubbles in flowing liquid due to sudden pressure drop is known as cavitation. These bubbles collapse as they move towards a higher pressure region against the turbine runner causing damage of the turbine surfaces and reduced efficiency of turbine [11]. The violent cavity collapses occur in a short time [65,66]. Different forms of cavities in a flowing liquid are travelling bubbles, partial cavitation vortices or attached cavities [67–69]. Due to cavitation and abrasive erosion, erosion of turbine takes place which causes production loss and unit outage [11]. Cavitation damages the turbine setup and material surfaces with excessive vibrations and flow instabilities and it ultimately degrades machine performance [54,69]. Cavitation can appear on different locations depending on the operating conditions of a machine [69–71]. Cavitations present themselves in conflict of metallic uppermost layer of turbine parts due to cavities. Reaction turbines
are greater liable to cavitations. Cavitations cause erosive corrosions, heavy vibrations and decrease in turbine efficiency and output. Cavitations can be continuously monitored by installing the vibration sensors on the outer wall of the unit, guide vane axes, support pedestal and/or at the maintenance door of draft tube [53].

When tips of the vapor filled vortices come in contact with solid surface, potential erosion takes place. Part load operation causes vortex cavitations in flow channels. Partial cavitations are a complex and common type of cavitations. The interface of cavity is turbulent and wavy. Large clouds of cavities and U-shaped transient cavities collapse violently on the solid surface [72]. In this type of cavitations high erosion occurs. Corrective steps are difficult to apply in existing units, so monitoring these cavitations during operation is the only solution to avoid harmful situations. Cavitations can be decreased by increasing the runner speed and operating the turbine within specified operating condition. Cavitation takes place at off design operating condition of turbine [69]. Collapsing of vapor cavities makes high frequency noise. Ultrasound method is the most suitable for measuring vapor cavities [73]. Cavitation erosion creates considerable negative effects on hydrogenerating equipment due to hydrodynamic mechanism. Operating in the damaging region can be avoided by detecting the cavitations correctly [74].

Cavitation causes heavy fluctuating forces. During cavitation, a pressure fluctuation takes place due to bubbles growth and collapse and causes vibrations in hydraulic turbines. This causes variation in flux distribution in stator. The cavitation vibration is of high frequency from several hundred cycles to several thousand cycles per second leading to system instability [51]. The suitable sensor to monitor the cavitation of high/medium frequency is accelerometer. The cavitation erosion splits in damage mechanism and hydraulic mechanism. The interface between these two is known as cavitations’ aggressiveness. In a turbine, the audio bandwidth of cavitations is from 3 kHz to 15 kHz [74–76]. Ultrasound method is more suitable for vapor cavitations measurement. These cavitation measurements are more credible and accurate [74]. Hydrodynamic pulsations due to cavitations cause changes in flow [20,77]. According to Prof. D. Thoma, the region of cavitations in reaction turbines can be determined by a dimensionless number known as Thoma’s cavitations factor [64,78].

Thoma’s cavitations factor \( \frac{H_s}{H_b} \) = \( \frac{H_b - H_s}{H_b} \) where \( H_b \) = barometric pressure of water head in meter, \( H_s \) = distance of turbine runner above tail water level in meter, \( H \) = water net head of turbine in meter.

Injection of compressed air into low-pressure regions softens the effect of cavity collapses and minimizes great damage. In bulb turbines, cavitations can be avoided by deciding the operation range [51]. Cavitations cannot be avoided completely, they can only be minimized to an acceptable level [62]. Precautions to be taken to reduce cavitations [79] have been given below.

- Periodic inspection of turbine parts and runner,
- As per manufacturer’s note, turbine should not be run below the minimum discharge,
- Operating the turbine according to supplier’s guidelines,
- Turbine proper submergence and
- Using cavitations resistant runner material.

4.4. Generator vibration

High rating motors and generators face abnormal vibrations due to winding looseness or shorts [5]. When winding insulation loses its dielectric strength inter turn faults occur in electric machines. Early detection of inter turn faults is desirable to protect the machine. These inter turn faults can also be detected in field circuit [80–82]. Increase in the number of incipient faults causes major breakdown of the machine [83]. An analysis of transient behavior of stator winding faults in synchronous machines is described in [84,85]. Reasons for imbalanced magnetic forces [7] have been mentioned below.

- Non uniform of air gap between rotor and stator,
- Insulation failure of any field pole,
- Unequal loading of generator,
- High partial discharge, and
- Loose windings.

It is difficult to diagnose the condition of mechanical vibration in a generator [11]. Inter-turn faults in the rotor and stator windings are commonly due to different sources those cause vibrations [43], [86]. According to [87] vibration related faults are from stator core and rotating field and greater vibration damages the stator bar insulation system. The time domain models to detect and estimate the stator inter turn faults were described in [2,88]. In generator fields vibration occurs due to mechanical imbalances and changing field. More electromagnetic forces make it difficult to control the vibration of the stator winding. The vibration between iron core and the bar is not prevented by insulation systems. Abnormal vibration of stator frame and stator core can damage the winding insulation. This happens when the air gap is not uniform causing disturbances in air gap torques, temperature rises, and imbalanced flux densities [50], [51]. Such faults can be predicted before causing serious damage using low-frequency vibration measurement on stator core and frame [4].

In [89] authors concluded that for a machine supplied at \( f_{se} = 50 \text{ Hz} \), vibration at or near 50, 100 and 200 Hz is indicative of eccentricity, but there is a confusion because other anomalies also manifest themselves with the production of such frequencies, for example, misalignment and dynamic imbalance. It is shown in [28] that for a machine supplied at \( f_{se} = 50 \text{ Hz} \), the stator frame vibration exhibits 100, 200 and 300 Hz components because of inter-turn winding faults or supply imbalance, including single phasing. Eccentricity in stator frame causes production of higher order harmonics. The theoretical review was carried out in [82,89,90] between mechanical vibration and electrical winding parameters under different operating conditions for a given fault of dominant frequencies. Coupling misalignment and imbalance worsen the situation [89]. Inter-turn stator winding faults cause even orders of fundamental frequency in vibration spectrum. The concept of principal time harmonics for eccentricity was explained in [89,91,92]. Inter-turn faults on a typical motor and a hydro generator have been shown in Fig. 7(a) and (b).

An inter-turn fault in the rotor winding causes magnetic imbalance, thermal imbalance and vibration with mechanical rotating frequency. Rotor vibrations change the magnetic permeance of air-gap with rotor mechanical rotating frequency. Stator vibration increases with this rotor mechanical rotating frequency and reaches a value twice the rotor mechanical rotating frequency because of inter-turn fault in the rotor. However the rotor vibration characteristic is different from stator vibration [43]. Stator frame and stator core vibrations cause high noise, core and stator vibration at unacceptable levels and cracks in the frame.

Sources of the imbalanced magnetic pull of the air gap and its effect on vibration are examined by many authors [95]. In the rotor eccentricity, calculation of harmonics to re-center the rotor and imbalanced magnetic pull were shown in [89,96]. The magnetic field of Air gap is the medium for transmitting the rotor vibration to the stator and the bearings. So bearing responses should also be considered along with rotor system. Accelerometers are more
suitable for higher frequencies and proxy-meters are suitable for lower frequencies as mentioned in [8].

5. Mechanical imbalance

Mechanical imbalance [16,97] may be due to various reasons; some of which are mentioned below.

- Winding looseness,
- Bearing Wear,
- Foundation looseness,
- Misalignment,
- Skid deformation,
- Coupling looseness,
- Shaft fatigue,
- Rotor eccentricity,
- Casing vibration,
- Rotor imbalances.

Reasons for vibration at various locations and remedies to overcome the problem have been described in Table 1.

Aerodynamic Sources are turbulence, ventilation fans and blade passing [16]. Electromagnetic Sources as per [16] have been given below.

- Static air-gap eccentricity,
- Dynamic air-gap eccentricity,
- Air gap permeance variations,
- Short or open windings,
- Imbalanced phase currents,
- Broken rotor bars,
- Torque pulses,
- Magnetostriiction.

6. Vibration monitoring and measurements

As mentioned earlier, VCM technique is very useful for timely identification of the fault due to excessive vibration [11,98]. The vibration measurement points of the hydro generator and the hydro turbine have been shown in [14].

6.1. Review of vibration Monitoring methods

In 1880, Curie discovered charge output and piezo effect sensor. In 1923, for the first time, an accelerometer was used. Over the last several years, this scientific knowledge has been developed to lead quick as well as efficient measurements of vibration [12]. Dial gauges were used for vibration measurement; but they did not give a complete idea of shifting of shaft position or motion of shaft center lines under different operating conditions. Shaft vibrations are measured using non-contact probes in two mutually perpendicular directions. The signal of this shaft vibration is recorded and analyzed for dominant frequencies by arranging it on X and Y-axis to get some idea on the condition of the equipment [5]. Vibrations of HPS are corresponding to pumping, turbine rough operating zone, turbine up thrust place, reciprocation to resonance effects, imbalanced air gap, changes of bearing oil viscosity, mechanical distortion effects, or any integration of these all as per [25]. Signal acquisition and processing is required to distinguish the vibration fault in HPS equipment which normally varies depending upon the nature of the fault [3].

VCM of the equipment in a plant gives the correlation between recorded vibration data and its mechanical condition. Proper VCM analysis facilitates to detect the equipment degradation prior to damage. Vibration occurs when the natural frequency of a machine shaft matches with the frequency components of fluctuations [51]. When the vibration level is above permissible limits, sources of vibrations should be identified and proper action should be taken to bring it within safe limits [7]. Condition monitoring and fault diagnostics are involved with the following steps.

- Signal acquisition.
- Signal analysis.
- Signal storage.
- Data transfer and storage.
- Data selection.

### Table 1

<table>
<thead>
<tr>
<th>Vibration area</th>
<th>Possible reasons</th>
<th>Remedies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor vibration</td>
<td>Rotator Imbalance, Shaft Misalignment, Swing of hydraulic forces, Generator Eccentric magnetic pull, Forces in labyrinth seal, Instability in bearings oil, Seal rubs.</td>
<td>Balancing the rotating parts, Increase stiffness of foundation, Connections and/or bearing brackets, Changing the number of runner blades, Changing the vibrating Stiffness components. Controlling the turbine operating range, Modifying the blade trailing edge, Replacing the old runner. Surge at draft tube, Injecting air between the wicket gates and runner, Replacing the old runner, Injecting air in the draft tube.</td>
</tr>
<tr>
<td>Wicket gates, stay vanes and runner blades vibration</td>
<td>Trailing edge vortex shedding of the vanes, Gate/blade interaction.</td>
<td></td>
</tr>
<tr>
<td>Vibration in the draft tube</td>
<td>Cavitations at runner blade, Surge at draft tube.</td>
<td></td>
</tr>
</tbody>
</table>
The vibration signal from equipment contains the information of machine running condition and they can be measured on the surface of the equipment. Vibration signal analysis instruments use Fast Fourier Transform (FFT), which converts vibration signal domain representation to its frequency domain representation. This is known as frequency spectra. If a machine is in good condition while running, vibration frequency spectra will have a particular shape which will get changed when faults occur. This is due to some undesirable signals mixing with the output signals. Hence, specialized signal processing is needed for analysis of these spectra [13].

Time waveform is the scheme of amplitude vs. Time where as Fast Fourier Transform is the plot of amplitude vs. frequency. Both are required to determine and analyze the fault after which maintenance is scheduled.

The process control systems like PLC, DCS, and SCADA are reliable for alarm and monitoring the vibration levels of HPS equipment [12]. Generally, vibration signal frequency ranges from 0 Hz to 40 kHz. In a time domain signal analysis any small change in vibration leads to change of amplitude with time [99].

The LabVIEW can also be used for VCM of an HPS. The American National Instruments Corporation provides LabVIEW, i.e. a development platform on graphical programming language. In this, signal processing of the digital filters, frequency domain analysis, time domain analysis, orbit track analysis, wavelet reconstruction and decomposition of signals can be processed [53], [100].

Vibration can be measured on a periodic basis but online measurements are better for continuous observation which allows more time for working personnel to take decisions so as to prevent any equipment or system to be stopped. Machine vibration health may be changed due to Water induction, Misalignment, Balance etc. as per [101]. The maintenance programs of HPS using VCM enable periodic to real-time condition based maintenance in a more economical and effective manner [11].

The vibration monitoring and fault diagnosis of large turbo generators were described in detail in [102]. Off-line and on-line computer analysis techniques for vibration [103] and change of fundamentals of machine were explained in [104]. The latest techniques on signal processing on vibration analysis have been described in [8,105,106].

6.2. On-line monitoring

On-line VCM control network was described in [11,107]. It detects the abnormal vibration situation at an early stage and accordingly fault modes get isolated. Correct interpretation and timely processed data lead to improvement in quality, waste reduction and safer operation. Vibration signal data need to be processed and de-noised for useful information. So VCM is carried out in frequency and time domain with natural and significant frequencies [99]. Currently, on-line condition monitoring and diagnostic give information to on-site working personnel and to control room display as well [108]; On-line VCM can detect shaft misalignment, bearing damage, shaft imbalance etc. with different generator data. Vibration information is necessary for finding the health of hydro power generator. Different vibration sensors used to monitor the hydro power generator are accelerometers, audio microphones, and eddy current proximity probes [109]. For VCM of the wind turbines different techniques and methods are developed [110–112]. Supervisory control and data acquisition system can also be part of condition monitoring, but they are not suitable for spectral analysis of some machines [113]. The following are the different online condition monitoring techniques those were described in literature in the past.

- Online condition monitoring using current and voltage measurements for wind turbine brake system fault diagnosis,
- Remote online equipment condition monitoring,
- Real-time condition monitoring for aircraft maintenance, and
- Hydro power plants condition-monitoring system.

Recently, wireless sensor networks (WSN) condition monitoring has been established [114]. Installation of WSN system is very flexible to make [6,115]. The advantages of on-line monitoring of Hydro generating equipment have been mentioned below.

- Operation and maintenance cost can be reduced.
- Risks to the person can be reduced.
- According to system parameters, equipment can be replaced.
- Major breakdowns can be minimized.
- Life and efficiency of equipment can be improved.
- Outage frequency can be minimized.
- Machine can be operated until the vibrations are within the limits.

Online VCM is very necessary in power plants which are being affected by silt, as vibrations in such plants increase rapidly [7]. Reliability improves with proper diagnosis and the cost benefits of on-line vibration condition based monitoring of an HPS are as follows [11].

- Maintenance cost: decreases 50–80%
- Breakdown of equipment: decreases 50–80%
- Downtime of machine: decreases 50–80%
- Overtime cost: decreases 20–50%
- Life of machine: increases 20–40%
- Profit: increases 25–30%

6.3. Off-line monitoring

In this technique, maintenance is normally scheduled at regular or irregular basis as corrective or preventive maintenance. The disadvantages of this method [11] have been given below along with a comparison between On-line and Off-line methods in Table 2.

- Huge production losses due to unplanned outage and shutdown,
- Waste of revenue and resources as maintenance is carried out even if the machine does not require it,
- Compromising on safety and environmental aspects, and
- Increase in the cost of preventive maintenance.

Table 2  

<table>
<thead>
<tr>
<th>Parameters</th>
<th>On-line method</th>
<th>Off-line method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Advantages</td>
<td>Periodic Shutdown test</td>
</tr>
<tr>
<td>Turbine Maintenance</td>
<td>1) Prevention of cavitations which are associated with abnormal vibration. Otherwise, these abnormal vibrations initiate alarms or shutdown of the unit accordingly. 2) Avoids system outages.</td>
<td>1) Cavitation damages can be detected only after the unit gets stopped, dewatered and visually inspected. 2) Waste of more time and manpower. 3) Cost of repair of erosion is more if damage increases due to delay in shutdown.</td>
</tr>
<tr>
<td>Maintenance</td>
<td>On-line monitoring is carried out with permanently installed sensors.</td>
<td>Periodic visual inspections should be done.</td>
</tr>
</tbody>
</table>
7. Standards for vibrations used in hydrogenerating equipment

Standards used for vibration measurement, Hitachi’s suggestion for turbines with different rpm and Russian practices of vibration have been given below in Tables 3–5 respectively.

8. Future prospectus of VCM

8.1. Studies on on-line vibration Monitoring under sensor fault

As vibration condition monitoring is a closed loop automated control system sensors play a big role in it. This automated control system needs to be studied under sensor faults. The sensor faults may be of open circuit, gain faults and saturation effects. All the three faults in the sensors will have disturbed the accuracy of the control systems. One of the authors of this paper has recently studied the effects of sensor faults in an induction motor drive, found the system stability and the requirement of extra capacitors in the DC link [117]. The double channel control system is recommended to maintain the accuracy and reliability of electro-mechanical equipment serving to hydro power plants.

8.2. Effects of tail race water pressure

There are a few possibilities to have the tailrace in power plants which are unable to discharge the used water into the river. This creates back pressure towards draft tube and hence turbine assembly. During this period, automatic generation control can be done using some optimization techniques [118]. The detailed study of such cases will also help to policy makers/power plant authorities during the planning of new projects as well.

8.3. Minimization of the cost of VCM

Significant investments are required to have the automatic vibration condition monitoring in an educational institution. Reduction in the cost of VCM helps to install such systems in educational institutions so that graduate students could be trained in a better way.

8.4. High speed VCM systems

There is significant scope for research to design a high speed VCM, which helps to increase the sensitivity of vibrations occurring in HGE. Such high speed VCM will also be helpful to minimize the damage due to unexpected mechanical/electrical faults in generator systems.

8.5. Shaft to ground voltage (SGV)

As discussed vibration sensors serving to VCM are usually mounted on the surface of HGE (both horizontal and vertical). Shaft to ground voltage that exists in synchronous generator may disturb the accuracy of VCM. Appropriate study needs to be done to analyze the effects of SGV on VCM.

9. Conclusion

The paper has presented a comprehensive review on VCM applied to Hydro Generating Equipments (HGE) and the future prospectus of VCM used in hydro power stations. Vibration on rotating and non-rotating parts of HGE the sensors used for the components are discussed. Various standards used for on-line and off-line condition monitoring of HGE are provided. From the

---

Table 3
Standards used for vibration measurement in Microns (peak to peak) [7].

<table>
<thead>
<tr>
<th>Speed (RPM)</th>
<th>J.H.Walker’s Book</th>
<th>B.S.2613 Value</th>
<th>T.P.E. Practice</th>
<th>VDI-2059</th>
<th>Generator Bearing Bracket</th>
<th>Generator Slip Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth Value</td>
<td>Fair Value</td>
<td>Smooth Value</td>
<td>Fair Value</td>
<td>Smooth Value</td>
<td>Fair Value</td>
<td>Smooth Value</td>
</tr>
<tr>
<td>166.6</td>
<td>70</td>
<td>170</td>
<td>N.A.</td>
<td>150</td>
<td>200</td>
<td>170</td>
</tr>
<tr>
<td>200</td>
<td>62</td>
<td>160</td>
<td>200</td>
<td>N.A.</td>
<td>N.A.</td>
<td>155</td>
</tr>
<tr>
<td>300</td>
<td>50</td>
<td>150</td>
<td>N.A.</td>
<td>125</td>
<td>NA</td>
<td>125</td>
</tr>
</tbody>
</table>

Table 4
Hitachi’s suggestion for different rpm turbines at Kotla, Bhakra Left & Ganguwal power station [7].

<table>
<thead>
<tr>
<th>Vibration Measurement Location</th>
<th>Normal Value</th>
<th>Maximum Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing Support</td>
<td>&lt;270</td>
<td>225</td>
</tr>
<tr>
<td>Draft Tube</td>
<td>&lt;30</td>
<td>30</td>
</tr>
<tr>
<td>Shaft Vibration</td>
<td>&lt;40%</td>
<td>33%</td>
</tr>
<tr>
<td>Vibrations with 0.2 mm gap</td>
<td>&lt;80</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 5
Russian practices [116] of vibration in Microns (Peak to Peak):

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Speed</th>
<th>Excellent</th>
<th>Good</th>
<th>Satisfactory</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>62.5</td>
<td>0–50</td>
<td>50–100</td>
<td>100–160</td>
<td>0.160</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>0–40</td>
<td>40–90</td>
<td>90–140</td>
<td>0.140</td>
</tr>
<tr>
<td>3</td>
<td>187</td>
<td>0–40</td>
<td>40–90</td>
<td>90–140</td>
<td>0.140</td>
</tr>
<tr>
<td>4</td>
<td>214</td>
<td>0–30</td>
<td>30–80</td>
<td>80–130</td>
<td>0.130</td>
</tr>
<tr>
<td>5</td>
<td>250</td>
<td>0–30</td>
<td>30–80</td>
<td>80–130</td>
<td>0.130</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
<td>0–20</td>
<td>20–70</td>
<td>70–120</td>
<td>0.120</td>
</tr>
</tbody>
</table>
review, it is found that monitoring is essential for shaft and bracket vibrations in a hydro turbine and relative shaft vibration, bearings absolute vibration, thrust bearing axial vibration, stator core vibrations, stator bar vibrations, stator end winding vibrations are significant in a hydro-generator. Non-contact capacitive proximity probes is used for dynamically monitor the motion of the generator turbine shaft relative to the bearings. Low-frequency accelerometers are used to monitor the absolute vibration of the bearings and of the turbine cover. Adaptation of an advanced vibration monitoring system shall be resulted increase in plant reliability. Vibration in draft tubes due to improper discharge of tail race water is identified as a common problem in existing power stations.

Acknowledgment

This work is supported by Tehri Hydropower Corporation India Limited vide Grant number THD-811-WRC (2014). The authors also would like to thank the editor and anonymous reviewers for their comments to improve this paper.

References


[16] D. Basak, A. Tiwari, S.P. Das, J. Merchant, Condition monitoring of hydro turbine cover. Adaptation of an advanced vibration monitor/turbine shaft relative to the bearings. Low-frequency accelerometers is used for dynamically monitor the motion of the generator turbine cover. Adaptation of an advanced vibration monitoring system shall be resulted increase in plant reliability. Vibration in draft tubes due to improper discharge of tail race water is identified as a common problem in existing power stations.

Acknowledgment

This work is supported by Tehri Hydropower Corporation India Limited vide Grant number THD-811-WRC (2014). The authors also would like to thank the editor and anonymous reviewers for their comments to improve this paper.

References


