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Review

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

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ABSTRACT

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.

Contents

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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 equipments 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, on-line 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 hydroelectric 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.

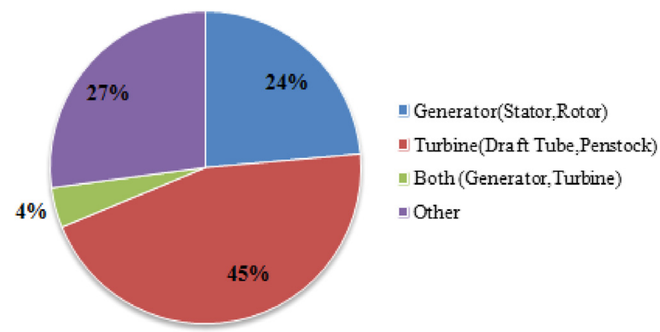


Fig. 1. Pie chart showing the distribution of papers covered in this review.

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

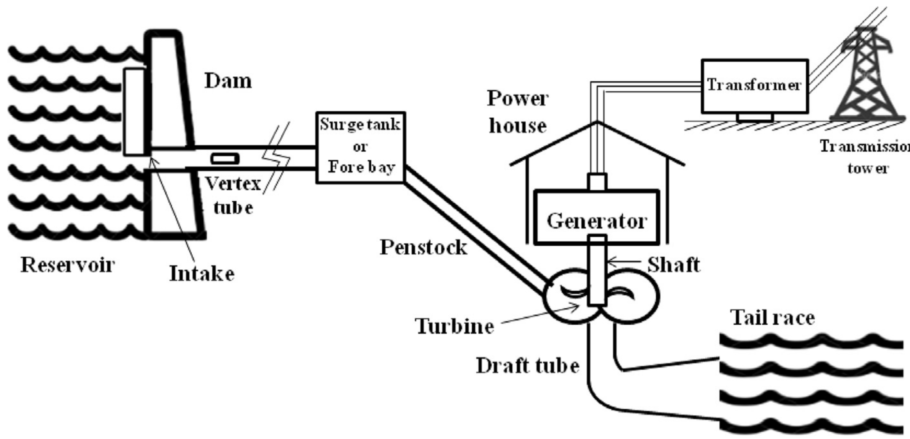


Fig. 2. Components of HPS.

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).

$$f_e = \frac{(f_s \times P)}{2} \tag{1}$$

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-

(a) (b)

Fig. 3. Francis Turbine Cavitations Damage (a) [18] and (b).[19].

tions. It can be noted that applying hydraulic excitation force is not a complete solution to minimize the vibration in turbine assembly when it is affected by cavitation. Suitable stiffeners should be added in the machine foundation to ensure natural frequency of the turbine assembly [20].

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 loosing 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).

$$F_v = 2f \pm f_r \tag{2}$$

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

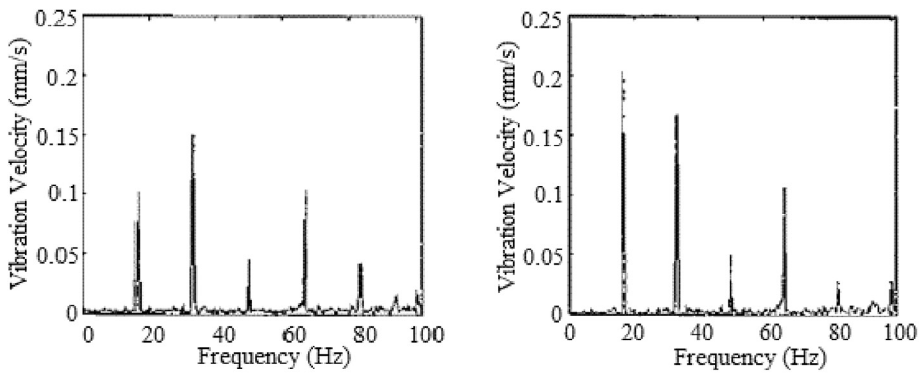
This case indicates that the machine feet are not coplanar with base or shims are not installed properly. This soft foot condition leads to excessive vibration, dynamic stress and distortion. Due to the combination of electromagnetic and mechanical stresses, electrical faults and break down in stator 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

(a) (b)

Fig. 4. Turbines (a) Misalignment detection [37] and (b) Breakage of wicket gate linkage [38].



(a) (b)

Fig. 5. Vibration Frequency Spectrum Characteristic of Rotor (a) before and (b) after fault.[43].

[13]. It also leads to bearing failure and overheating [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 [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 [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 [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 [40,41]. On-line detection of these faults first described in 1971 [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% [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 [43]. In [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 built either as an integral part or exposed above the dam structure. Penstocks must have good hydraulic performance, minimum water leakage and stability in its structure [46]. The penstock vibration depends upon local hydraulic conditions in the area surrounding penstock outlets and on the dynamic properties when filled with water [47]. Sudden change in water flow generates water hammer which is the critical issue in the penstock [48]. Change in water flow may be occurring due to unit start up, shut down, operational errors, operating mode changes, load rejections and load variations [49]. System failure or penstock collapse may occur due to this water hammer [46]. Water hammer pressure causes oscillations in a hydroelectric plant [50]. During a full load rejection, guide vanes face water hammer which ultimately affects the turbine efficiency [51]. Cavitations or erosion inside the penstock cause vibrations those are due to high velocity, turbulent water flow, or scouring damage [52].

Pressure fluctuations in flow passage are harmful to machine stability since they cause output power oscillations, vibrations, resonance of HPS foundations, tears inside draft tube and blade cracks. Pressure fluctuations can be revealed by low-frequency swirls inside draft tubes, flow separations in penstocks, Von Karman vortex and inter blade vortex [53]. In penstocks, the vibration may be equipment induced or flow induced. This vibration causes material fatigue which may lead to problems in penstock. Maintenance personnel should inspect the penstock and mark the abnormal vibration. Excessive vibration can be noticed along with its amplitude and frequency using VCM technique [52].

Further, to prevent water hammer, protection devices like pressure relief valves, surge tanks, intake gates, air chambers and air valves, load and flow control equipment such as turbine wicket gates, penstock control valves and governor should be inspected periodically for proper operation [46,54]. Water hammer is not a problem for short length of penstock [55]. A computer program named WHAMO, developed by U.S. Army Corps of Engineers, can be used to simulate mass oscillation and water hammer in penstocks and water conduits [52].

4.3. Draft tube vibration

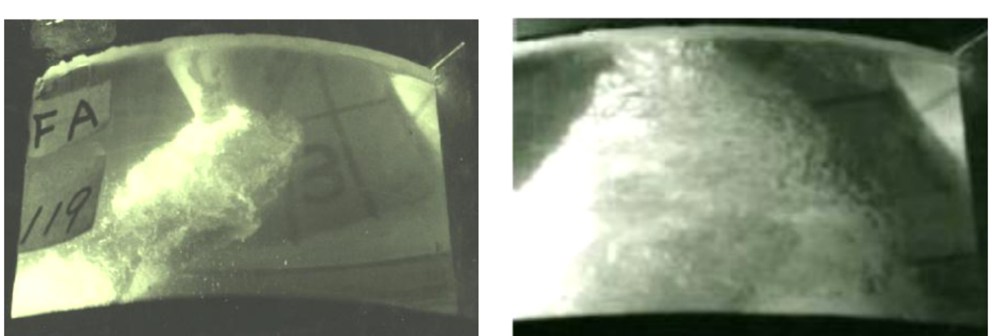
Draft tube vibration is the most interesting phenomenon which causes great obstruction to operation of Francis turbine. This is due to flow instability associated with overload or part load operation of the turbine. Swirling flow causes a vortex inside the draft tube. Draft tube surges cause vibrations, 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 filtering 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 detailin [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



(a) (b)

Fig. 6. Vortex at Turbine during (a) Partial Load and (b) Overloads.

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 hydro-generating 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 $= (H_b - H_s)/H$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 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 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 [8,28,90] 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 eccentric was explained in [8,28,91,92]. 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 [8,89,96]. 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

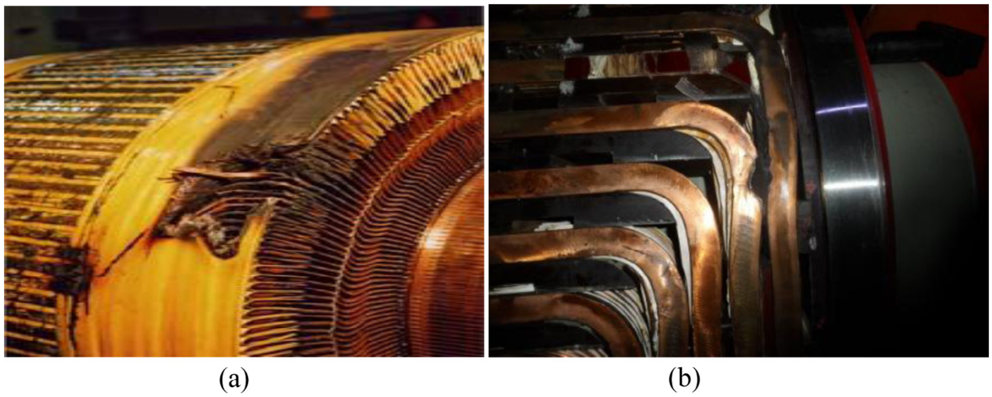


Fig. 7. Inter-turn faults on (a) Motor [93] and (b) Hydro generator (300 MW).[94]

suitable for higher frequencies and proxy-meters are suitable for lower frequencies as mentioned in [8].

5. Mechanicalimbalance

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,
- Magnetostriction.

Table 1
Reasons for vibration and their remedies [56].

Vibration area	Possible reasons	Remedies
Rotor vibration	Rotor Imbalance, Shaft Misalignment, Swing of hydraulic forces, Generator Eccentric magnetic pull, Forces in labyrinth seal, Instability in bearings oil, Seal rubs.	Balancing the rotating parts, Increase stiffness of foundation, Connections and/or bearing brackets, Changing the number of runner blades, Changing the vibrating Stiffness components.
Wicket gates, stay vanes and runner blades vibration	Trailing edge vortex shedding of the vanes, Gate/blade interaction.	Controlling the turbine operating range, Modifying the blade trailing edge, Replacing the old runner.
Vibration in the draft tube	Cavitations at runner blade, Surge at draft tube.	Surge at draft tube, Injecting air between the wicket gates and runner, Replacing the old runner, Injecting air in the draft tube.

6. Vibrationmonitoring 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, Curies 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.

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
Comparison between On-line and Off-line methods [11] of vibration monitoring.

Parameters	On-line method		Off-line method	
	On-line monitoring	Advantages	Periodic Shutdown test	Limitation
Turbine Maintenance	Vibration Monitoring is carried out with permanently installed sensors.	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.	Periodic visual inspections should be done.	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.

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

Speed (RPM)	Maximum frame vibrations				Maximum shaft displacement			Generator			
	J.H.Walker's Book		As per VDI 2059 Part-1	B.S.2613 Value	T.P.E. Practice		VDI-2059	Bearing Bracket		Slip Ring	
	Smooth Value	Fair Value			General Value	Maximum Value		RanjitSagarPower Plant 4X150 MW	Dehar Power Plant 6X165 MW	RanjitSagarPower Plant 4X150 MW	Dehar Power Plant 6X165 MW
166.6	70	170	N.A.	–	150	200	170	120	–	–	NA
200	62	160	200	–	N.A.	N.A.	155	NA	–	–	NA
300	50	150	N.A.	125	N.A.	N.A.	125	NA	100	–	0.2 mm

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

Vibration Measurement Location	Normal Value		Maximum Value	
	166.6 rpm	300 rpm	166.6 rpm	300 rpm
Bearing Support	<270	<225	<450	<375
Draft Tube	<30	<30	<50	<50
Shaft Vibration	<40%	<33%	<56%	<50%
Vibrations with 0.2 mm gap	<80	<60	<112	<100

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

S.No.	Speed	Excellent	Good	Satisfactory	Poor
1	62.5	0–50	50–100	100–160	0.160
2	150	0–40	40–90	90–140	0.140
3	187	0–40	40–90	90–140	0.140
4	214	0–30	30–80	80–130	0.130
5	250	0–30	30–80	80–130	0.130
6	300	0–20	20–70	70–120	0.120

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 electromechanical 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 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 of discharge of tail race water is identified as a common problem in existing power stations.

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References

[1] A. Barbour, W.T. Thomson, Finite element study of rotor slot designs with respect to current monitoring for detecting static air gap eccentricity in squirrel - cage induction motors, in: Thirty-Second IAS Annual Meeting, IAS '97., Conference Record of the 1997, IEEE, IEEE Industrial Applications Society, 1, New Orleans, LA, 1997, pp. 112–119.
[2] S. Nandi, H.A. Toliyat, X. Li, Condition monitoring and fault diagnosis of electrical motors — a review, IEEE Trans. Energy Convers. 20 (2005) 719–729.
[3] D. Basak, A. Tiwari, S.P. Das, Fault diagnosis and condition monitoring of electrical machines – a review, in: IEEE International Conference on Industrial Technology (ICIT 2006), Mumbai, 2006, pp. 3061–3066.
[4] Mesa Associates, INC. and Oak Ridge National Laboratory, Hydro power Advancement Project, 2012, pp. 1–331.
[5] D.H. Shreve, Integrated Condition Monitoring Technologies, IRD Balancing LLC, Chester, UK, 2003, pp. 1–63.
[6] L. Selak, P. Butala, A. Sluga, Condition monitoring and fault diagnostics for hydro power plants, Comput. Ind. 65 (2014) 924–936.
[7] R.K. Aggarwal, Metal fatigue due to excess vibration and dynamic stresses on an hydro power station, available at <https://www.scribd.com/document/141411086/DynamicStressesHydroPowerPlantRKAggarwal/> downloaded on 3rd September, 2014.
[8] P.J. Tavner, Review of condition monitoring of rotating electrical machines, IET Electr. Power Appl. 2 (2008) 215–247.
[9] Z. Qiling, W. Hegao, Modal analysis of hydropower house by using finite element method, in: Asia-Pacific Power Energy Eng. Conf., 2009, pp. 1–4.
[10] S. Wei, L. Zhang, Vibration analysis of hydropower house based on fluid-structure coupling numerical method, Water Sci. Eng. 3 (2010) 75–84.
[11] I. Ahmad, A. Rashid, On-line monitoring of hydro power plants in Pakistan, Inf. Technol. J. (2007) 919–923.
[12] Online Industrial Vibration Analysis for Predictive Maintenance and Improved Machine Reliability, available at <www.ctconline.com>, downloaded on 10th September 2014.
[13] S.K. Singh, (Research Scholar, Dept. Of Mech. Engg., IITG), Acoustics Based Condition Monitoring, 1–07.
[14] D. Morris, Condition monitoring of hydroelectric plants, 2014, pp. 4–6. available at <http://www.emersonprocessxperts.com/2014/04/condition-monitoring-of-hydroelectric-plants/>, downloaded on 3rd September, 2014.
[15] V. Mircea, T. Radu, D. Danut, Critical analysis of vibration sources of hydro aggregates in operating regime, J. Sustainable Energy 2 (2011) 1–8.
[16] K. Wang, Vibration monitoring on electrical machine using vold-kalman filter order tracking, J. Vib. Control (2008) 1–122.
[17] H. Xue, H. Wang, P. Chen, K. Li, L. Song, Automatic diagnosis method for structural fault of rotating machinery based on distinctive frequency components and support vector machines under varied operating conditions, Neuro Comput. Elsevier 116 (2012) 326–335.
[18] Online Cavitations Damage, available at <www.en.wikipedia.org>, downloaded on 3rd September, 2014.
[19] Christopher Earls Brennen, Hydrodynamics of Pumps, Cambridge University Press, 2011.
[20] P. Sridharan, N. Kuppuswamy, Mitigation of vibration on bulb turbine in small hydro electric power plants, Int. J. Eng. Technol. 5 (2014) 4968–4979.
[21] J.R. Stack, T.G. Habetler, R.G. Harley, Effects of machine speed on the development and detection of rolling element bearing faults, IEEE Power Electron. Lett. 1 (2003) 19–21.
[22] P. Vas, Parameter Estimation, Condition Monitoring and Diagnosis of Electrical Machines, Clarendon, Oxford, U.K., 1993.
[23] B. Heller, V. Hamata, Harmonic Field Effects in Induction Machine, Elsevier, New York, 1977.
[24] J.R. Cameron, W.T. Thomson, A.B. Dow, Vibration and current monitoring for detecting air gap eccentricity in large induction motors, IEE Proc. B – Electr. Power App. 133 (1986) 155–163.
[25] J. Stein, Advanced condition monitoring of hydro generators knowledge base, Electr. Power Res. Inst. (1999) 1–58.
[26] D.G. Dorrell, W.T. Thomson, S. Roach, Analysis of air gap flux, current and vibration signals as a function of the combination of static and dynamic air gap eccentricity in 3-phase induction motors, IEEE (1995) 563–570.
[27] S. Nandi, S. Ahmed, H.A. Toliyat, Detection of rotor slot and other eccentricity related harmonics in a three phase induction motor with different rotor cages, IEEE Trans. Energy Convers. 16 (2001) 253–260.
[28] S. Nandi, R.M. Bharadwaj, H.A. Toliyat, Performance analysis of a three-phase induction motor under mixed eccentricity condition, IEEE Trans. Energy Convers. 17 (2002) 392–399.
[29] H.A. Toliyat, M.S. Arefeen, A.G. Parlos, A method for dynamic simulation of air-gap eccentricity in induction machines, IEEE Trans. Ind. Appl. 32 (1996) 910–918.
[30] A.J.M. Cardoso, E.S. Saraiva, Computer-aided detection of air gap eccentricity in operating three-phase induction motors by park's vector approach, IEEE Trans. Ind. Appl. 29 (1993) 897–901.
[31] N.A. Al-nuaim, H.A. Toliyat, A novel method for modeling dynamic air-gap eccentricity in synchronous machines based on modified winding function theory, IEEE Trans. Energy Convers. 13 (1998) 156–162.
[32] M. Haji, H.A. Toliyat, Rotor eccentricity fault detection of a DC motor, in: 27th Annu. Conf. IEEE Ind. Electron. Soc., C, 2001, pp. 591–596.
[33] R.J. Povinelli, J.F. Bangura, N.A.O. Demerdash, R.H. Brown, Diagnostics of bar and end-ring connector breakage faults in polyphase induction motors through a novel dual track of time-series data mining and time-stepping coupled fe-state space modeling, IEEE Trans. Energy Convers. 17 (2002) 39–46.
[34] H. Meshgin-kelk, J. Milimonfared, H.A. Toliyat, A comprehensive method for the calculation of inductance coefficients of cage induction machines, IEEE Trans. Energy Convers. 18 (2003) 187–193.
[35] R.R. Obaid, T.G. Habetler, D.J. Gritter, A simplified technique for detecting mechanical faults using stator current in small induction motors, IEEE (2000) 479–483.
[36] Electricity Engineers' Association of New Zealand, Asset Health Indicator Guideline for Generators, (2013) 1–72.
[37] Online Misalignment Detection, available at <http://en.wikipedia.org> downloaded on 3rdSeptember 2014.
[38] Online Breakage of Wicket Gate Linkage, available at <www.hydroworld.com> downloaded on 3rd September 2014.
[39] T.L. Wahl, Draft tube surging times two: the twin vortex phenomenon, Hydro Rev. (1994) 60–68.
[40] K.A. Khudabashev, Effect of turn short-circuits in a turbo-generator rotor on its state of vibration, ElektStantsii (Russian) 7 (1961) 40–45.
[41] L.T. Rosenberg, Influence of shorted turns on thermal imbalance in large generators IEEE, PES Summer Meeting, paper A78 (1978) 587–588.
[42] D.R. Albright, Inter-turn short circuit detector for turbine generator rotor windings, IEEE Trans. Power Appl. Syst., PAS-50 (1971) 478–483.
[43] W. Shuting, X. Zhaofeng, L. Yonggang, H. Zili, L. Heming, Analysis of generator vibration characteristic on rotor winding inter-turn short circuit fault, electrical machines and systems, IEEE (2003) 882–885.
[44] Z. Rongpei, Diagnosis of generator bearing vibration on rotor winding interturn short circuit fault, Therm. Power Gener. 2 (1994) 49–53.
[45] Z. Yubi, H. Shuisheng, Vibration analysis of shaft 10 for generator i in pingwei power plant, Electr. Power 33 (2000) 45–47.
[46] Mesa Associates, INC. and Oak Ridge National Laboratory, Best Practice Catalog Penstocks and Tunnels, (2012) 1–21.
[47] N.V. Khalturina, A.M. Bozhovich, Vibration of the penstock at the Baiina-Bashta dam on the drin river, Hydro Tech. Constr, Netherlands 8 (1972) 740–745.
[48] A. Bergant, A.R. Simpson, A.S. Tijsseling, Water Hammer with Column Separation : A Review of Research in the Twentieth Century, J. Fluid. Struct. 22 (2004) 135–171.
[49] Arun Kumar (AHEC, IITR), Automation in Water Resources and Hydro power Plants, (2008) 1–71.
[50] S. Pejovic, Q.F. Zhang, B. Karney, A. Gajic, Analysis of pump-turbine ' S ' instability and reverse waterhammer incidents in hydro power systems, in: 4th International Meeting on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems, 2011, pp. 1–16.
[51] P. Sridharan, N. Kuppuswamy, Vibration and cavitation prediction and control of turbine alternator in hydro electric power Plants, Aust. J. Basic Appl. Sci. 7 (2013) 19–28.
[52] B. Mcstraw, Inspection of steel penstocks and pressure conduits, Facil. Instr. Stand. Tech. 2 (1996) 1–43.
[53] Z. Liu, S. Zou, L. Zhou, Condition monitoring system for hydro turbines based on LabVIEW, in: Asia-Pacific Power and Energy Engineering Conference, Shanghai, 2012, pp. 1–4.
[54] P.P. Singh, S.K. Shukla, N. Pharlia, Operation & Maintenance Perspective of Hydro Electric Projects, 1–13.
[55] Natel Energy, The hydro Engine, 1–11.
[56] R. Susan-Resiga, T.C. Vu, S. Muntean, G.D. Ciocan, B, Nennemann jet control of the draft tube vortex rope in francis turbines at partial discharge, IAHR Symp. 1 (2006) 1–14.
[57] J.K. Harvey, Some observations of the vortex breakdown phenomenon, J. Fluid Mech. 14 (1962) 585–592.

[58] T.B. Benjamin, Theory of the vortex breakdown phenomenon, J. Fluid Mech. (1962) 593–629.
[59] T.B. Benjamin, Some developments in the theory of vortex breakdown, J. Fluid Mech. 28 (1967) 65–84.
[60] J.J. Cassidy, H.T. Falvey, Observations of unsteady flow arising after vortex breakdown, J. Fluid Mech. 41 (1970) 727–736.
[61] J. Arpe, F. Avellan, C. Nicolet, Experimental evidence of hydroacoustic pressure waves in a francis turbine elbow draft tube for low discharge conditions, J. Fluids Eng. 131 (2009) 1–9.
[62] H. Ohashi, Vibration and Oscillation of Hydraulic Machinery, Avebury Technical, 1991.
[63] R.H. Thicke, Practical solutions for draft tube instability, Water Power Dam Constr. 33 (1981) 31–37.
[64] P. Kumar, R.P. Saini, Study of cavitation in hydro turbines — A review, Renewable Sustainable Energy Rev. Elsevier 14 (2010) 374–383.
[65] F. Avellan, M. Farhat, Shock pressure generated by cavitation vortex collapse, in: Proceedings of the Third International Symposium on Cavitation Noise and Erosion in Fluid Systems, (1989) 119–125.
[66] A. Philipp, W. Lauterborn, Cavitation erosion by single laser-produced bubbles, J. Fluid Mech. 361 (1998) 75–116.
[67] F.G. Hammitt, Cavitation erosion state of art and predicting capability, Appl. Mech. Rev. (1979) 665–675.
[68] R.E.A. Arndt, Recent advances in cavitation research, Adv. Hydrosci. 12 (1981) 1–72.
[69] X. Escaler, E. Egusquiza, M. Farhat, Detection of cavitation in hydraulic turbines, Mech. Syst. Signal Process., Elsevier 20 (2006) 983–1007.
[70] F. Avellan, P. Henry, Towards the prediction of cavitation erosion: IMHEF research program, in: Proceedings of the EPRY Symposium on Power Plant Pump, 1987, pp. 1–22.
[71] P. Bourdon, R. Simoneau, P. Lavigne, A vibratory approach to the detection of erosive cavitation, in: Proceedings of the Third International Symposium on Cavitation Noise and Erosion in Fluid Systems, 88, 1989, pp. 103–109.
[72] F. Avellan, P. Dupont, I.L. Ryhming, Generation mechanism and dynamics of cavitation vortices downstream of a fixed leading edge cavity, in: Proceedings of the 17th Symposium on Naval Hydrodynamics, 1988, pp. 1–13.
[73] Tianhao, Study of cavitations monitoring in hydro power turbines using ultrasound, J. NDT 25 (2003) 250–253.
[74] S. Liu, S. Wang, Cavitations monitoring and diagnosis of hydro power turbine on line based on vibration and ultrasound acoustic, Mach. Learn. Cybern. (2007) 19–22.
[75] B. Bajic, Intelligent cavitations diagnostics and monitoring, Int. J. Hydro Power Dams 54 (2001) 37–41.
[76] B. Bajic, Cavitations diagnostics and monitoring, Int. J. Hydro Power Dams 56 (2003) 32–35.
[77] S. Watanabe, C.E. Brennen, Dynamics of a cavitating propeller in a water tunnel, J. Fluids Eng. 125 (2003) 283–292.
[78] R.K. Bansal, Fluid Mech. Hydraul. Mach. (1998) 839–841.
[79] Online Operation and maintenance of hydro power stations planning and management – an Indian perspective, available at <www.teriin.org>, downloaded on 10th September 2014.
[80] D.W. Auckland, I.E.D. Pickup, R. Shuttleworth, Y.T. Wu, C. Zhou, Novel approach to alternator field winding interturn fault detection, Proc. Inst. Electr. Eng.-Gen. Trans. Distrib. 142 (1995) 97–102.
[81] R.J. Streifel, R.J. MarksII, M.A. El-Sharkawi, I. Kerszenbaum, Detection of shorted-turns in the field winding of turbine-generator rotors using novelty detectors development and field test, IEEE Trans. Energy Convers. 11 (1996) 312–317.
[82] J.S. Hsu, J. Stein, Shaft signals of salient-pole synchronous machines for eccentricity and shorted-field-coil detections, IEEE Trans. Energy Convers. 9 (1994) 572–578.
[83] G.B. Kliman, W.J. Premerlani, R.A. Koegl, D. Hoeweler, A new approach to on-line turn fault detection in AC motors, IEEE 1 (1996) 687–693.
[84] X.H. Wang, Y.G. Sun, B. Ouyang, W.J. Wang, Z.Q. Zhu, D. Howe, Transient behaviour of salient-pole synchronous machines with internal stator winding faults, IEEE Proc.-Electr. Power Appl. 149 (2002) 143–151.
[85] P. Neti, S. Nandi, Stator interturn fault detection of synchronous machines using field current and rotor search-coil voltage signature analysis, IEEE Trans. Ind. Appl. 45 (2009) 911–920.
[86] L. Yonggang, L. Heming, Zhaohua, H. Zili, C. Deling. A new method on inter turn short circuit fault diagnosis of steam turbine generator rotor windings, in: 15th International Conference on Electrical Machines, 2002.
[87] C.V. Maughan, Vibration detection instrumentation for turbine-generator stator endwindings, IEEE Electr. Insul. Conf. (2009) 173–177.
[88] X. Chang, V. Cocquempot, C. Christophe, A model of asynchronous machines for stator fault detection and isolation, IEEE Trans. Industr. Electron. 50 (2003) 578–584.
[89] R.B. Rai, Airgap eccentricity in induction motors, ERA Report (1974) 1174–1188.
[90] F.C. Trutt, J. Sottile, J.L. Kohler, Detection of AC machine winding deterioration using electrically excited vibrations, IEEE Trans. Ind. Appl. 37 (2001) 10–14.
[91] D.G. Dorrell, W.T. Thomson, S. Roach, Analysis of airgap flux, current, and vibration signals as a function of the combination of static and dynamic airgap eccentricity in 3-phase induction motors, IEEE Trans. Ind. Appl. 33 (1997) 24–34.
[92] W.T. Thomson, A. Barbour, On-line current monitoring and application of a finite element method to predict the level of static airgap eccentricity in three-phase induction motors, IEEE Trans. Energy Convers. 13 (1998) 347–357.
[93] Dr. Antony Anderson, Electrical Fault and Failure Investigations online available at: <www.antony-anderson.com>, downloaded on 1st August 2014.
[94] Online Inter Turn Fault, available at <www.wbpdclewf.org.in>, downloaded on 20thSeptember 2014.
[95] K.J. Binns, M. Dye, Identification of principal factors causing imbalanced magnetic pull in cage induction motors, Proc. IEE 120 (1973) 349–354.
[96] S.A. Swann, Effect of rotor eccentricity on the magnetic field in the air-gap of a non-salient-pole machine, Proc. IEE 110 (1963) 903–915.
[97] Online Increases Availability in the Hydro Power Industry, available at <www.rovsing-dynamics.com>, downloaded on 1st August 2014.
[98] B. Bajic, J. Sabolek, D.J. Dvekar, D. Magic, Vibration, Air gap and Magnetic Flux Investigation in the HPP Dubrava Bulb Unit 1, in: 4th Symposium on Power System Management, Cavtat, Croatia, 2000 and 1st International Symposium Hydroelectric Power Plants HEPP 2001,Sibenik, Croatia, 2001.
[99] G.Y. Luo, D. Osypiw, M. Irle, Real-time condition monitoring by significant and natural frequencies analysis of vibration signal with wavelet filter and autocorrelation enhancement, J. Sound Vib. 236 (2000) 413–430.
[100] National Instruments, Lab VIEW: Getting Started with Lab VIEW, 2003.
[101] M. Nord, B. Broussard, Online Vibration Monitoring System Offers Foresight on Turbine Condition, Pulp Paper (2005) 46–49.
[102] I.W. Mayes, Use of neutral networks for on-line vibration monitoring, J. Power Energy (1994) 267–274.
[103] R.G. Herbert, Computer techniques applied to the routine analysis of rundown vibration data for condition monitoring of turbine-alternators', Br. J. Non-Destr. Test. 28 (1986) 371–375.
[104] M.G. Smart, M.I. Friswell, A.W. Lees, Estimating turbogenerator foundation parameters: model selection and regularization, in: Proc. R. Soc., Math., Phys. Eng. Sci., 2000, pp. 1583–1607.
[105] A. Saleh, A. Kazzaz, G.K. Singh, Experimental investigations on induction machine condition monitoring and fault diagnosis using digital signal processing techniques, Electr. Power Syst. Res. Elsevier 65 (2003) 197–221.
[106] G.K. Singh, S.A. Kazzaz, S. Ahmed, Vibration signal analysis using wavelet transform for isolation and identification of electrical faults in induction machine, Electr. Power Syst. Res. Elsevier 68 (2004) 119–136.
[107] Y. Wang, F. Sun, T. Huang, Development of on-line VCM system of hydro generators, in: Proceedings of the Third International Conference on Machine Learning and Cybernetics, 2004, pp. 1025–1029
[108] U. Kunze, Condition telemonitoring and diagnosis of power plants using web technology, Prog. Nucl. Energy, Elsevier 43 (2003) 129–136.
[109] B. Lloyd, Condition Monitoring of Hydro Generators, IEEE Power Engineering Society Summer Meeting, Edmonton, Alta, 2, 1999, pp. 996–998.
[110] F. Pedro, G. Marquez, A.M. Tobias, J.M.P. Perez, M. Papaelias, Condition monitoring of wind turbines : techniques and methods, Renewable Energy, Elsevier 46 (2012) 169–178.
[111] M. Entezami, S. Hillmansen, P. Weston, M.P. Papaelias, Fault detection and diagnosis within a wind turbine mechanical braking system using condition monitoring, Renewable Energy, Elsevier 47 (2012) 175–182.
[112] Bureau of Reclamation – Hydroelectric Research and Technical Services Group, Facilities Instructions 4-1A, Maintenance Scheduling for Mechanical Equipment, Denver, Colorado, 2009.
[113] W. Yang, R. Court, J. Jiang, Wind turbine condition monitoring by the approach of SCADA data analysis, Renewable Energy, Elsevier 53 (2013) 365–376.
[114] Y. Yang, G. Xie, X. Xu, Y. Jiang, A monitoring system design in transmission lines based on wireless sensor networks, Energy Procedia, Elsevier 12 (2011) 192–199.
[115] M.J. Chae, H.S. Yoo, J.Y. Kim, M.Y. Cho, Development of a wireless sensor network system for suspension bridge health monitoring, Autom. Constr., Elsevier 21 (2012) 237–252.
[116] L.A. Vladislavlev, A. Jaganmohan, V.S. Kothekar, Vibration of Hydro Units in Hydroelectric Power Plants, Amerind Publishing Company, 1979.
[117] D. Arun Dominic, T.R. Chelliah, Analysis of field-oriented controlled induction motor drives under sensor faults and an overview of sensorless schemes, ISA Trans. 53 (2014) 1680–1694.
[118] R.K. Sahu, T.S. Gorripotu, S. Panda, Automatic generation control of multi-area power systems with diverse energy sources using Teaching Learning Based Optimization algorithm, Eng. Sci. Tech., Int. J. 19 (2016) 113–134.