CAUSES OF VIBRATION AND THEIR TREATMENT IN HYDRO POWER STATION

Kuldeep Singh[1], Dr. D.K. Bhalla[2]
[1]B.Tech. Mechanical Engineering (Evening) Scholar, School of Mechanical Engineering, Lingaya's Vidyapeeth, Faridabad, Haryana, India
[2]Professor and LEET Coordinator B.Tech., M.Tech., PhD, FIE in Lingaya's Vidyapeeth, Faridabad, Haryana, India

***Abstract*— By reducing the likelihood of damage and breakdown, vibration condition monitoring (VCM) improves the operation of hydro-generating equipment (HGE) and extends its lifespan. The theoretical and experimental exploitation is involved in the VCM execution and system diagnosis of an HPS. Numerous investigations have contributed to our understanding of the vibration failure mechanism and early stages of HPS breakdowns. This study reviews vibration monitoring and correction (VCM) of electrical and mechanical equipment used in the HPS and provides a short description of vibration related issues based on about three decades of historical publications. The requirements for vibration measurements and the causes of vibrations on HPS's rotating and non-rotating equipment have been covered. There is also discussion on VCM's future prospectus.**

***Index Terms*— VCM, HPS, HE, Vibration Failure mechanism etc**

I. INTRODUCTION

Since the inception of electricity production, Hydro electricity Stations (HPS) have had a significant issue with equipment vibration. In hydro power stations (HPS), equipment failure brought on by vibration may result in shutdowns or, in extreme cases, catastrophic events [1,2]. To check the state of complex systems in hydropower generating and to automatically assess the operation of such equipment live, VCM is required. Relative shaft vibration, absolute bearing vibration, turbine cover vibration, thrust bearing axial vibration, stator core vibrations, stator bar vibrations, and stator end winding vibrations are just a few of the hydrogenating equipment components for which HPS offers online vibration monitoring. Typically, non-contact capacitive proximity sensors are used to dynamically track the movement of the turbine/generator shaft in relation to the bearings. The probes must be impervious to mechanical surface defects on the shaft, magnetic fields, and electrical run-out. Typically, low-frequency accelerometers are used to monitor the turbine cover's and the bearings' absolute vibration. The system design for vibration data processing from vibration probes is made possible by an online programmable digital processing unit that is multi-channel and multi-tasking. Selecting VCM is crucial as it offers early warning of approaching failure. This allows for the easy detection of any flaw or abnormal state prior to the device tripping by any technical expert. As a result, resources may be preserved and needless maintenance can be avoided. This essay addresses different vibration sources and how to address them. Although there have been many prior research on this subject, a study of all those studies is necessary to have a deeper understanding of the vibration-related problems. This study provides a quick overview of the VCM by presenting material from many available literatures. Vibration levels may be used to determine a machine's condition. The other approaches with more research potential include vibration signal processing and fault detection techniques. The HGE vibrates due to a variety of reasons, including hydraulic, mechanical, and electrical ones [3]. These vibrations have many complex and probably inevitable origins. The required actions to be made for safe and stable operation include inspecting these reasons and addressing them early on. The most hazardous stressors experienced by an HPS are vibrations, which happen when wicket gates suddenly open or close. By analysing the vibration transients of an existing HPS, detrimental resonances that may arise at a plant are prevented, increasing the equipment's availability and dependability. The VCM provides information about the impending failure and may be inferred in the shortest amount of time. With experimental research for support, this study offers a thorough overview of the subject. Fig. 1 displays the distribution of research article publications included in this study. However, there are also a number of professional bodies and groups that are related to this field, such as the International Energy Agency (IEA), Task Committee ASCE, IEEE Standard 492TM-1999, BIS Standard IS-12800 (Parts I, II, and III), 1991, IEEE Guide for the Rehabilitation of Hydroelectric Power Plants, and so on. Their contributions are extremely significant in the field of HPS condition monitoring.

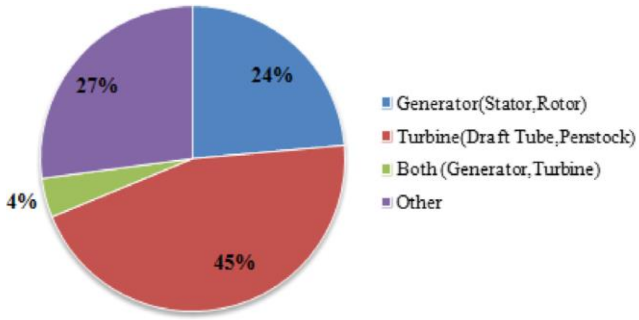


Figure 1: Pie chart illustrating how the articles included in this review were distributed.

Vibration at the turbine guide bearing and generator may be used to identify various causes of imbalance, bearing issues, wicket gate issues, and shear pin failure. The best method for locating machine flaws is vector content multiplicity (VCM) [4,5], which selects input and output using signal processing and data collecting. Data capture and sensors coupled to the necessary equipment may be used to monitor high frequency events [6]. The guide vanes, runner blades, rim, bearing, shaft seal, shaft, runner labyrinth, loose or shear nuts, wedges, stampings, bolts, pole wedges, etc. at the impacted places all suffer wear and tear as a result of excessive vibrations. Equipment has to be replaced often due to fatigue failure and fast wear and damage [7]. Excess noise might also result from excessive vibrations.Root causes of the fault sequence [8] in failure mode are provided by VCM. Vibration investigations heavily rely on finite element analysis [9, 10].

II. VIBRATIONAL SOURCES

Several HPS components are shown in Fig. 2. Here, the most crucial and expensive electro-mechanical equipment is the turbine, generator, and power transformer [11]. Certain vibration frequencies are produced by the spinning components. The vibration amplitude of a machine or piece of equipment defines its quality and performance. The rotating components lead to more serious issues as the vibration amplitude rises [12].

The primary causes of vibration [7] are listed below.

Three types of vibrations: hydraulic, mechanical, and electrical.

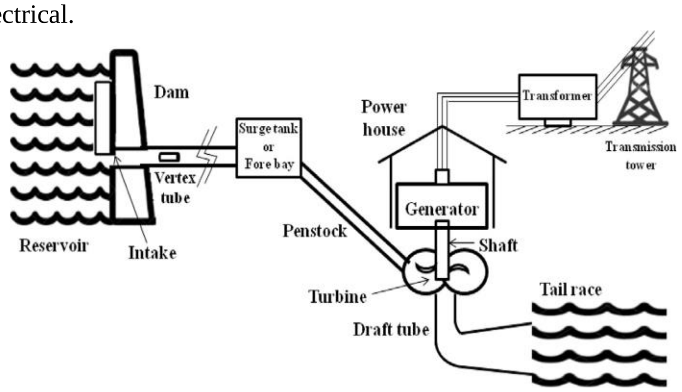


Fig. 2. HPS Components.

Not only spinning equipment but even non-rotating equipment may experience vibrations. The following is a list of causes for the vibrations on different pieces of equipment.

A. The causes of vibrations in spinning machinery

- Turbine runner:

The following factors might be causing the vibrations on the turbine runner. These include misalignment, cavitations, mechanical and hydraulic imbalances, harsh zone operation, insufficient lubrication of mechanical components, damaged bearings, breakage of the wicket gate linkage, and cracked or chipped shaft and blades in turbine bearings that are unstable owing to rubs and hydraulic stresses [13].

- Rotor:

In addition to the causes listed for the runner, rotor rubs may also be the cause of vibrations on the rotor [14].

B. Causing factors for equipment vibrations that do not rotate

- Draft tube resonance, power swings, and cavitations.
- Seal erosion: Water quality affects this.
- Cavitations in the Penstock resonance
- Electromagnetic force is the generator.
- Magneto motive forces in the transformer

The three primary causes of vibration in both the generator and the turbine are mechanical looseness, recirculation, and abrasive erosion [11–15]. Transformers, electric motors, turbines, and generators are the main sources of vibration. By detecting the vibration signal with sophisticated instruments, these devices can identify and diagnose malfunctions.

III. EQUIPMENT FOR PRODUCING HYDROELECTRICITY VIBRATING

This section provides a detailed illustration of the causes of vibration on rotating hydro producing equipment, including motors, turbines, and generator rotors.

A. Engines

There are three types of motor vibration: aerodynamic, mechanical, and electromagnetic. The causes of mechanical issues include imbalances and misalignments.

- Looseness,
- Impact or fretting,
- Defective bearings,
- Winding damage from mechanical shock, etc.

The cause of aerodynamic issues is Ventilation fans, broadband turbulence, resonant volume excitations inside the motor, discrete blade passing frequencies, etc.

Disproportionate electromagnetically driven forces on the rotor and stator cause vibrations associated with electrical malfunctions. Air gap eccentricity, fractured rotor bars, uneven flux distribution in the air gap, inter-turn faults, open or shorted stator and rotor windings, uneven phase currents, magnetostriction, and torque oscillations are the causes of this imbalance [16]. Equation (1) provides a mathematical expression for the relationship between rotational frequency and electrical supply frequency [7].

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

where P is the number of magnetic poles, fe is the electrical supply frequency, and fs is the shaft rotational frequency.

B. Windmills

Extreme force variations brought on by cavitations are the source of hydraulic turbine vibrations. The frequency at which resonance arises in the foundation and turbine supporting structure may be determined using VCM. Hydrodynamic pulsations and cavitation-induced vibration in hydro turbines are caused by pressure differences created by massive cavities [17]. Cavitations alone are the primary cause of erosive wear in turbines. Fig. 3 illustrates the damage caused by cavitations to a Francis hydro turbine. To reduce resonant vibrations, hydraulic stimulation force must be avoided rather than altering the natural frequencies. It should be noted that when a turbine assembly is impacted by cavitation, using hydraulic excitation force alone is not a sufficient way to reduce vibration. In order to guarantee the turbine assembly's natural frequency, appropriate stiffeners have to be included into the machine foundation [20].

(a) (b)

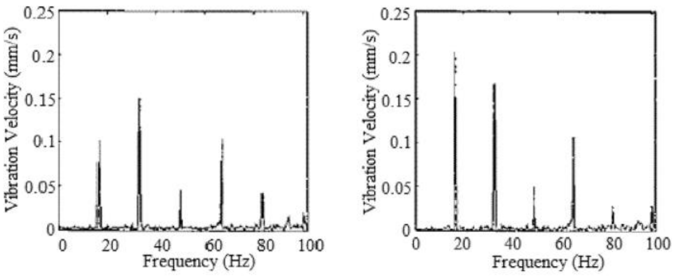
Figure 3. Cavitations Damage to Francis Turbines (a) [18] and (b).[19].

Overheating and bearing failure are additional consequences. There are two types of shaft misalignment:

offset and angular. In the event that it is angular, there is a difference in angle between the moving machine and the stationary machine's shaft centre line in the horizontal and vertical planes. As stated in [5], this angle is 0 degrees for any stationary machine. Fig. 4(b) illustrates how misalignment may break the wicket gate connection.

(a) (b)

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



(a) (b)

Fig. 5 The vibration frequency spectrum characteristics of the rotor before and after the defect

IV. EQUIPMENT FOR PRODUCING HYDROELECTRICITY THAT VIBRATES

A. Switching

Both the core and the windings vibrate due to the magneto driving force. These vibrations are linked to a noise that is twice as frequent as the supply, such as buzzing. As these vibrations rise, the transformer's performance decreases. Vibration pads and correct transformer internal component mounting may help minimise this vibration, while it cannot be totally eradicated.

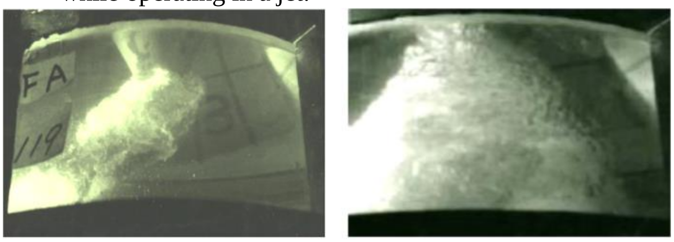
B. Penstock

Penstock is a pipe that is pressurised and is used to move water from the reservoir to the turbine. Penstock may be constructed above the dam construction or as an integrated element. Penstocks need to be structurally stable, have little water loss, and have high hydraulic performance. The dynamic characteristics when filled with water and the local hydraulic conditions around penstock outlets determine the penstock vibration. The main problem with the penstock is the water hammer that is produced by a sudden shift in water flow. The starting up and stopping of the unit, operational problems, switching operating modes, load rejections, and load fluctuations may all cause changes in the flow of water. This water hammer may cause penstock collapse or system failure. In a hydroelectric plant, oscillations are caused by water hammer pressure. Guide vanes encounter water hammer during a full load rejection, which eventually reduces turbine efficiency. Vibrations in the penstock are caused by erosion or cavitations, which are caused by scouring damage, turbulent water flow, or high velocity.

C. Vibration of the draft tube

The most fascinating phenomena that seriously impedes the Francis turbine's ability to operate is vibration in the draft tube. This results from flow instability brought on by the turbine operating at overload or partial load. Within the draft tube, a vortex is created by swirling flow. Penstock pressure surges, power swings, vibrations, and noise are all caused by draft tube surges. In addition to reducing efficiency, cavitation may harm the turbine, erode metal, or force the machine to shut down. Cavitations may be identified by detecting the vibration of the draft tube and turbine using an accelerometer and signal filter. In this dangerous area, the device should not be used [4]. Details on the vortex rope in the draft tube using the jet control technique were provided in the Francis turbine's part load operation. Below are some benefits of the vortex rope jet control approach.

- No runner adjustments are needed; no extra devices need to be installed within the draft tube.
- It may be turned off when not in use and modified in accordance with the operational point.
- It is easy to use and sturdy
- The turbine's overall efficiency remains constant while operating in a jet.



(a) (b)

Figure 6: Vortex at Turbine under Partial and Overload Conditions

D. Vibration of the generator

Unusual vibrations in high-rated motors and generators are caused by loose or short windings [5]. Electric devices experience interturn problems when winding insulation begins to lose its dielectric strength. To safeguard the machine, interturn defects should be detected as soon as possible. Field circuits are another place where these interturn defects may be found. A significant machine failure is caused by an increase in the frequency of early problems [83]. This paper describes an examination of the transient behaviour of stator winding defects in synchronous machines. Below is a list of causes causing uneven magnetic forces [7].

- Inconsistent air gap between the stator and rotor;
- Any field pole insulation failing;
- Inequitable generator loading;
- Elevated partial discharge; and
- Loose windings

(a) (b)

Figure 7 shows inter-turn failures on a motor and a 300 MW hydro generator.

V. Unbalance Caused by Machinery

There are many possible causes of mechanical imbalance [16], some of which are listed here.

- Wear on the bearings,
- Winding looseness,
- Loose foundation,
- Skid deformation,
- Misalignment,
- Loose coupling,

Shaft fatigue, eccentricity of the rotor, cascading vibration, and rotor imbalances. Table 1 lists the causes of vibration at different places along with solutions to the issue. Turbulence, ventilation fans, and blade passage are examples of aerodynamic sources [16]. Below are the electromagnetic sources listed in accordance with [16].

- The eccentricity of the static air gap, the dynamic air gap,
- Variations in air gap performance
- Open or brief windings,
- Inequitable phase currents
- Torque pulses; fractured rotor bars; magnetostriction.

Table 1: Vibration causes and their fixes.

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.

VI. MEASUREMENTS AND MONITORING OF VIBRATIONS

As was already indicated, the VCM approach is very helpful in quickly identifying the issue caused by excessive vibration [11,98]. The hydro generator and hydro turbine's vibration measurement locations are shown in [14].

A. An analysis of vibration monitoring techniques

Curies made the discoveries of charge output and piezo effect sensor in 1880. The earliest application of an accelerometer occurred in 1923. This scientific understanding has advanced over the last several years to enable rapid and effective vibration measurements [12].

While vibration was measured using dial gauges, the motion of the shaft centre lines and the changing of the shaft location under various operating situations were not fully understood by the dial gauges. Non-contact probes are used to monitor shaft vibrations in two directions that are perpendicular to one other. In order to get an understanding of the equipment's condition, the signal from this shaft vibration is collected, examined for prominent frequencies, and arranged on the X and Y axes [5]. Pumping, the turbine's rough working zone, the turbine's up thrust point, reciprocation to resonance effects, unbalanced air gaps, variations in the viscosity of the bearing oil, mechanical distortion effects, or any combination of these may all cause HPS vibrations. To identify the vibration fault in HPS equipment, signal collecting and processing are necessary and often rely on the kind of defect [3]. An equipment's mechanical state and recorded vibration data are correlated by the vibration monitoring system (VCM) in a plant. An accurate VCM analysis makes it easier to identify equipment deterioration before harm occurs. When the inherent frequency of a machine shaft coincides with the frequency components of oscillations, vibration occurs. Sources of vibrations should be found and appropriate action should be made to reduce the vibration level to within safe bounds when it exceeds allowable limits [7]. The subsequent procedures entail fault diagnoses and condition monitoring.

VII. NORMS FOR VIBRATIONS IN HYDROELECTRIC MACHINERY

The vibration measuring standards, Hitachi recommendations for turbines with varying revolution rates, and vibration practices in Russia are listed in Tables 3–5, respectively.

Table 3: Microns (peak to peak) vibration measurement standards [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 recommendation for various rpm turbines at the Bhakra Left and Ganguwal power plants

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: Vibration procedures in microns (peak to peak) used in Russia

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

VIII. VCM'S FUTURE PROSPECTUS

A. Online vibration studies monitoring while a sensor malfunctions

Since vibration condition monitoring is an automated control system operating in a closed loop, sensors are crucial to its operation. Under sensor failures, this automated control system has to be examined. Open circuits, gain problems, and saturation effects are possible types of sensor defects. The precision of the control systems will have been compromised by all three of the sensor malfunctions. Recent research by one of the paper's authors on the consequences of sensor failures in induction motor drives revealed the need for additional capacitors in the DC connection as well as system stability. For the electromechanical equipment supporting hydropower plants to remain accurate and reliable, a double channel control system is advised.

B. Tail race water pressure effects

Power plants that are unable to release their spent water into rivers have a few options for where to store their tailrace. Back pressure is therefore created in the direction of the draft tube and the turbine assembly. Using certain optimisation approaches, automated generation control may be carried out throughout this time. Policy makers and power plant authorities will benefit from a thorough analysis of these situations when developing future initiatives.

C. Reduction of VCM expenses

For an educational institution to have automated vibration status monitoring, significant expenditures are needed. Lowering the cost of VCM makes it possible for educational institutions to deploy these systems and provide graduate students with better training.

D. Rapidly operating VCM systems

The design of a high speed VCM, which aids in raising the sensitivity of vibrations occurring in HGE, has a great deal of room for investigation. Such a fast VCM will also be useful in reducing the harm caused by unforeseen electrical or mechanical failures in generating systems.

E. Shaft to ground voltage (SGV)

As previously mentioned, vibration sensors that support VCM are often installed on the outside of HGE, both vertically and horizontally. The accuracy of the VCM may be affected by the synchronous generator's shaft to ground voltage. Analysing the impact of SGV on VCM requires the right research.

IX. CONCLUSIONS

The study provided a thorough analysis of VCM as it relates to hydro generating equipment (HGE) and the potential applications of VCM in hydroelectric power plants in the future. Discussion is held on vibration on both revolving and non-rotating HGE sensor components. There are many standards available for both online and offline HGE condition monitoring. According to the review, vibrations in the shaft and bracket of a hydro turbine must be monitored, and vibrations in the stator core, stator bar, relative shaft, thrust bearing axial vibration, absolute bearing vibration, and stator end winding vibration are important in a hydro-generator. To dynamically monitor the motion of the generator or turbine shaft in relation to the bearings, non-contact capacitive proximity probes are used. The turbine cover and the bearings' absolute vibration are tracked using low-frequency accelerometers. The use of an advanced vibration monitoring system is expected to enhance the dependability of the facility. Inefficient tail race water discharge from power plants is known to often cause vibration in the draft tubes.

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/conditionmonitoring- 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