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Research Article

Effect of Cavitation with Vibration on the Powerhouse Structure of Bulb Turbines Installed in Hydropower Stations

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Hydro energy is one of the world's most abundant and valuable renewable electricity sources. Hydropower is an important source since it is a clean, sustainable, and cost-effective source of energy. The most perilous characteristic that affects the performance of the hydraulic turbine and its allied parts is the cavitation phenomenon, which is clear as the increase of vapor bubbles in the liquid through any hydraulic turbine. Cavitation causes vibration, which is very harmful to turbine guide bearings and their supporting structures. Sometimes heavy vibration causes cracks in the civil structure of the powerhouse where the bulb turbines are installed. The performance of the bulb turbine and the stability of the powerhouse structure are studied with the effect of cavitation, vibration, and deformation of the turbine casing. Experimental measurements are used to determine at what force the shape of cavitation is very destructive and crucial when the local pressure is less than the vapor pressure of the flowing water, at which static pressure cavities begin to breed and ruin. This paper focuses on small hydropower stations with bulb turbine installations, which emphasized the performance improvement of these turbines by avoiding cavitation on the runner blades. Allowing some cavitation on these machines is also recommended, which is within repairable condition, and the cavitation pitting can be repaired during annual maintenance.

1. Introduction

Modern years have seen a steady rise in the amount of grid-connected wind, solar, and other electricity generated as a result of a favorable environment and an on-demand energy market. Instability in the grid's functioning has been caused by the over-penetration of intermittent energy [1]. As a result of this expectation, customers are more or less confident that they will be capable of drawing a bigger or less quantity of grid electricity as needed, and they suppose the grid to accommodate this. Hydro turbines of the future must be able to generate a variety of forms of energy [2]. The hydroturbines must function outside the specified area, with recurrent start-stop and ramping. There are certain issues associated with power production under off-design loads [3] like differences in pressure, vortex fluctuations, and the inception of cavitation and resonance. Hydro turbines may be able to attain a high ramping rate by operating at constant speeds [4].

Constant-speed turbines have the runner's rotational speed constant and operate along with a synchronous speed line. The guiding vane opening controls the power output. Two factors may be employed to operate the turbine best in variable-speed mode: water passing through guide vanes and the speed of the runner. The synchronizing operation brings the input frequency to 50 Hz before joining with the grid to achieve speed variation [5]. In order to bind, the effects of vortex fluctuation, resonance, live loading, rotational swiftness, and flow rate may be accustomed. It is possible to enhance performance in nondesign circumstances [6]. Cavitation is one of the most essential issues since it causes erosion and lowers the efficiency of hydro turbines.

Pressure and temperature distress a liquid's thermodynamic phase. The tensile tension that occurs among the molecules of water is affected by its peaks and valleys in the above parameters. During cavitation, which happens when the tensile pressure is superior to the leaping force, molecules breakdown apart and the water converts into a vapor, creating a cavity [7]. The cavitation formation may be uniform or mixed, liable to the existing environment. For example, in hydro turbines, nuclei progress on the other side of the runner vane or at the borderline between liquid and inner particles, representing mostly heterogeneous nucleation. Hydro turbine cavitations consist of transit bubble formation and it continues until it bursts at the higher-pressure region [8]. Many experts have researched turbine cavitation during the last two decades. For example, cavitation-caused erosion and the creation of nuclei, high-frequency vibrations, and noise were all examined in the investigations. Adjustable speed and starting-stopping cavitation are significantly unlike cavitation under stable circumstances of the runner or added simpler situations, such as hydrofoils [9]. As a result of less environmental value and low operating and maintenance charges for the world's electricity source, hydroelectric power plants are the utmost important renewable energy source. Hydraulic power has a lot of promise that has yet to be realized. Hydroelectricity is one of the most environmentally friendly and long-term clean energy sources available. Because hydroelectric power facilities do not consume fuel and do not contaminate the air, they do not emit greenhouse gases. They help to avert global warming by taking preventative measures. Hydroelectric power accounts for roughly 16% of global electricity output. Thermal power facilities harm the environment more than hydroelectric power plants. The quantity of energy produced by a water source in a hydropower plant is determined by the amount of water and the water head. The turbine type to be employed is decided by these two primary characteristics. The different types of turbines are separated into two classes: impulse turbines and reaction turbines [10]. The turbine type to be employed is decided by these two primary characteristics. The different types of turbines are divided into two categories: impulse turbines and reaction turbines. In comparison to the reaction turbine, the modification of the runner blades in the bulb turbine is adjustable and able to be moved about the pivots fixed to the runner boss. Hydraulic machinery Cavitation causes undesirable outcomes such as water disturbances, severe vibrations, surface quality damage, and machine performance loss [11]. If the vigor in any region of a hydraulic turbine's hydraulic flow, which is in the way of travel amidst the governing blades or the turbine blades, falls underneath the water's evaporation pressure, the water in that region will evaporate, resulting in the development of vacuum volumes occupied with saturated water vapor inside. High volume impacts induced by the influence of water droplets on the surface at a very great speed degrade the material surface by creating it to disintegrate when they enlarge and increase following the general fluid motion and then unexpectedly disappear [12].

2. Cavitation in Hydro Turbines

Cavitation in hydraulic machinery has objectionable effects, for instance flow instabilities, excessive vibrations, material surface damage, and machine performance loss. Inappropriately, these problems are fetching added seriousness as the intensity of cavitation rises. The first and primary requirement for increasing the output power of a turbine is based on shrinking its size to diminish the cost of its components. Hence, the cavitation number is decreased and the speeds are increased.

Subsequently, due to the deregulation of the hydropower generation sector, there is a good trend to run turbines in settings away from the finest competence position, and cavitation events are most likely brought beneath away from setting values. As a result, the combined effect of these elements increases the likelihood of cavitation issues in hydraulic machinery. Because correction methods are not easy to implement in operating units, observation and operating methods that detect cavitation during operation and help to overcome dangerous circumstances are the finest option.

The methods for detecting cavitation are based on the machine's caused vibrations and pressures. Because hydropower generation is unaffected, this strategy is advantageous. These detection approaches are created using a basic understanding of the cavitation phenomenon and will be employed in actual prototypes. As a result, due to cavitation, it can take many forms and ascend in innumerable areas depending on the machine's working circumstances, and hence its proper application becomes more complicated [13].

Cavitation happens when vapor bubbles form in a liquid as a result of a hydraulic turbine. Dynamic pressure fluctuations can occur in hydro turbines. When the local pressure drops below a certain level, vapor pressure cavities form as well as grow. Formation and expansion are the two phases of such a hollow. When the pressure rises, the bubble's growth is reversed, and it suddenly bursts. Reference [14].

The succeeding effects on hydraulic machinery are caused by the cavitating flow: Low-pressure cavities formed amongst the guiding vane blades and the turbine runner lowered the cross-sectional area. As the discharge and power shrink, so does the cross section area shrink. The efficiency of the turbine declines from 5% to 10% when the bubbles break. The inner surface of the turbine casing will be eroded by cavitation erosion. Such damaged surfaces grow as a result of continuous cavitation. When erosion rates increase, material particles come out from the inner surface. Cavitation causes unstable radial hydraulic forces on the turbine runner and in turbine-generator guide bearings. Vibration and oscillation are caused by these instabilities, which are harmful to the above bearings [15]. With partial load, large vortex cavitation occurs in the draught tube, which lowers the competence of the draught tube and hence the turbine extends from 2% to 5%.

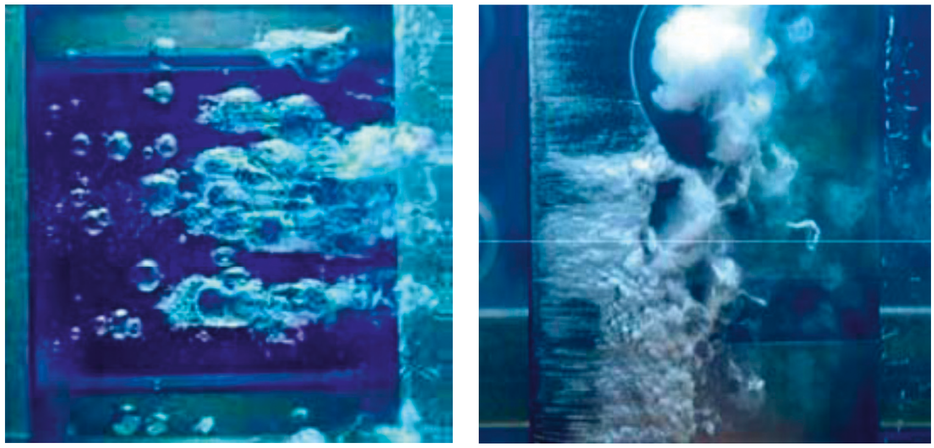
(a) (b)

Figure 1: 2D hydrofoil cavitation: (a) travelling bubbles; (b) unstable attached sheet.

2.1. Travelling Bubbles. Bubbles are formed that cover the body with very small and tiny nuclei in the vacuum regions of the flow shown in Figure 1. The breakdown is when they come into an unfavorable pressure gradient while traveling with the flow. The amount of air in the liquid has a big impact on these bubbles. Their erosive power, however, is supposed to be relatively feeble. The premise that a lonely bubble will continue spherical in an infinite liquid can be used to represent it [16]. The Universal Rayleigh–Plesset equation is a lawful estimation growth of the bubble in this situation, and it is resolved to obtain the bubble dimensions.

$$\frac{P_B(t)-P_\infty(t)}{\rho}=R_B\frac{d^2R_B}{dt^2}+\frac{3}{2}\left(\frac{dR_B}{dt}\right)^2+\frac{4v}{R_B}\frac{dR_B}{dt}+\frac{2\gamma}{\rho R_B}. \quad (1)$$

Figure 2: Travelling bubble cavitation.

In the form of separated bubbles, these bubbles are related to the vacuum side of the blade in the middle of the runner vane adjacent to the trailing edge. Due to the low Thomas number, these traveling bubbles begin to progress, and they expand in size when the machine is overloaded and operating at its greatest flow rate [17]. According to Figure 2, (a) kind of cavitation causes substantial machine downtime and even leads to blade erosion.

2.2. Vortex Cavitation. Vortices advances in water-flowing areas with cavitation formation due to the vacuum. The vortices make a potentially erosive atmosphere since the cavity's bursting of bubbles occurs on them when the tips of these vortices with vapor content come into touch with a solid face. This sort of cavitation can form if Von Karman vortex-shedding happens at the end of the hydrofoil where the pressure becomes a vacuum, as shown in Figure 3. This results in lift fluctuations in lockstep with the frequency of shedding. When hydraulic equipment is functioning at part load, cavitation due to vortex can happen in the water path. Vortices advance in water-flowing areas with cavitation formation due to the vacuum. This can cause exhaustion damage in the case of a natural frequency coupling phenomenon.

To progress in the channels between the blades, which in turn produces the vortex, the flow separation is caused by the occurrence of dissimilarities from the hub to the band, which causes secondary vortices. It is possible to fix them at the junction of the runner's top edge or midway between blades near the suction side of the crown [18]. When the tips of the runner vane are in contact with the blade area, they are capable of damaging the track. At low loads, these vortices emerge and provide a high amount of wideband noise. It is promising for them to look and cavitate at exceptionally high head operation ranges. This causes them to become unbalanced, resulting in a significant quantity of shaking.

Compared to Francis turbines, Kaplan turbines have a lower risk of leading-edge cavitation. When running in on-cam mode, the machine's runner vanes have a changeable dimension. As a result, the draught tube swirl is more than in Francis turbines as well. Due to the greater blade loading, traveling bubble cavitation may also occur on the vacuum side of the runner vane. Tip vortex cavitation is a kind of Kaplan turbine cavitation that is all its own. The gap between the tip of the blade and the case is where the cavitation occurs [19]. This cavitation destroys a region along the middle portion of the blade at the suction side, due to the tip of the vortex meeting the runner vane area, as a result of which the tip of the vortex meets the runner vane area. The tip of the blade might also be eroded.

2.3. Draft Tube Swirl. Directly below the runner cone, is created the draught tube's cavitation vortex-core flow. On the left, the circumferential velocity of the flowing water is cleared from the blade, its volume is dependent on the plant cavitation factor and it occurs between a partial load to an overload condition. Vortices travel counterclockwise whereas under half load and clockwise when overloaded. The accurate speed of 0.25–0.35 times turbine rotational swiftness is seen in the vortex core from 50% to 80% of the finest proficiency flow rate. In this occurrence, the low frequency is used to produce pulsations of circumferential pressure. If the occurring frequency coincides with the draught tube's natural frequency oscillation if any, large variations result. The turbine and even the powerhouse are subjected to severe vibrations as a result of the pressure variation due to the bubble burst inside the draught tube [20]. The draught tube cone is axially centered once the vortex has passed the point of greatest efficiency. Large changes are caused because the occurring frequency and the draught tube's natural frequency oscillation are in the same phase. The vibrations are really strong around the turbine and even the powerhouse. The bubble inside the draught tube ruptured as a result of the pressure change.

3. Turbine Setting Level

The position H_s in Figure 4 that regulates the pressure with respect to the vapor pressure beginning is the machine's setting level. Highly depending on this level, bubble cavitation occurs even at the machine's highest efficiency point. The cavitation factor of a hydraulic turbine is influenced by the value [21]. The International Electrotechnical Commission (ICE) suggests using the Thoma number, often known as the plant cavitation numberσ_p, which is described as

$$\sigma_p = \frac{NPSE}{E},$$
$$NPSE = \frac{P_I}{\rho} + g\left(Z_I - Z_{ref}\right) + \frac{1}{2}C_I^2 - \frac{P_v}{\rho}, \quad (2)$$

$$NPSE = \frac{P_a}{\rho} - gH_s + \frac{1}{2}C_I^2 - \frac{P_v}{\rho}. \quad (3)$$

4. Effects of Cavitation

Cavitation vulnerability is a chief limit state in the present hydro turbine design. Cavitation enhances the opposing, corrosion, vibration, and fatigue of marine structures, according to research [22]. Furthermore, cavitation-induced vibration greatly increases noise generation, which is especially problematic for turbines positioned in the powerhouse structure. Figure 5 shows the Kaplan Turbine schematic diagram.

Figure 3: Von Karman vortex-shedding 2D hydrofoil.

The appearance of cavitation has a noteworthy impact on the system's power generation. In general, as ambient pressure drops, the lift and drag numbers of a hydrofoil do not change; pressures are caused on the lower surfaces as well as by a decrease in lockstep. The pressure on the top surface is constrained by the vapour pressure and cannot be reduced, nevertheless, as cavitation happens along the upper surface of the foil. On the other hand, the pressure on the lowest surface is not limited and continues to fall, progressively approaching that on the top of the foil. When the pressure differential across the foil reduces, the lift coefficient drops as well. Furthermore, the resulting shift in the geometry of the pressure scattering causes drags to rise. As a result, cavitation reduces lift and upturns drag, limiting power generation and worsening system loads.

To categorize cavitation in real-world machinery, measurement and analysis of brought-out signals are used. It's not a simple process to detect since the location, behavior, and method of formation of cavitation bubbles are different on the turbine specification and working environment. Due to the kind of excitation and the transmission channel to the sensor is affected by this. In addition, noise from additional excitation causes, such as hydrodynamic, mechanical, or electromagnetic, might simultaneously occur. When it comes to improving detection, selecting the right sensor and measurement location on the machine is very critical. Reference [23]. It is typical to practice conducting pressure measurements on a draught tube wall or on the pedestal of the turbine's guide bearing while doing vibration measurements on the guide vane arm. Measurements must also be taken under various operating circumstances to ensure that the machine's whole working range is monitored. It is also important that the observed signals are captured at the appropriate locations.

Hydraulic noise is measured and analyzed to learn more about cavitation's characteristics. Pioneer's work shows how this connection might be utilized in manufacturing applications like hydro turbines to monitor erosive cavitation in actual machinery [24]. When it comes to turbines, structure-borne noise is quite easy to quantify. Using fluid-borne noise is another option, although it is not always viable to place a

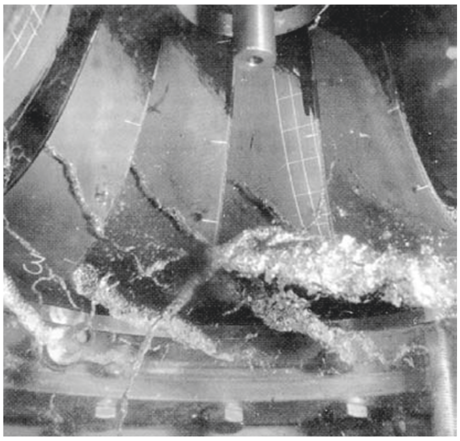

Figure 4: Interblade vortex cavitation.

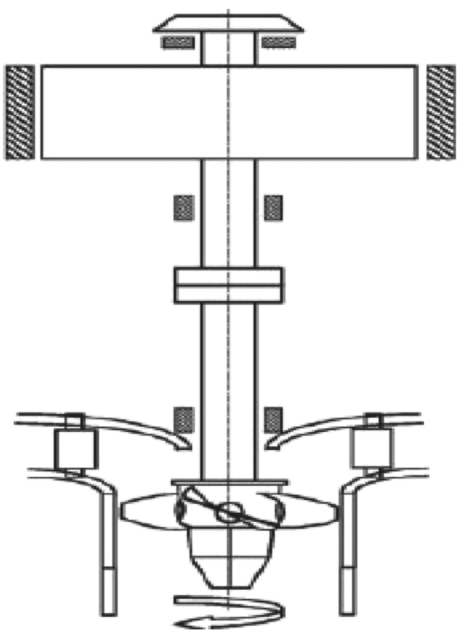

Figure 5: Kaplan turbine.

pressure sensor near the runner. As a result of signal attenuation during transmission, it is impossible to detect cavitation noise directly.

5. Theoretical Investigations

Hydraulic turbine damage is shown which is to be caused by cavitation difficulties, sand erosion, material faults, and fatigue in water turbines. Kaplan turbines' draught tube cones and runners are most vulnerable to cavitation. Improvements in hydraulic design and fabrication of mechanisms, the use of erosion-resistant materials, and the configuration of turbines to operate inside acceptable cavitation conditions were found to minimize cavitation erosion [25].

Detailed information on the source of pitting in the runner, cavitation repair techniques, cavitation pitting sites, repair procedures, and places of great stress in the runner. Areas of typical cavitation pitting have been discovered.

Using a vibratory technique, cavitation monitoring is done in hydraulic turbines. As a means of testing, a small change of the turbine's distributor is designed to lessen cavitation aggressiveness and hence the associated erosion, this approach was utilized in a big Francis turbine. Fixed components of the turbine prototype were tested for cavitation-induced vibrations and compared to identical and unrehabilitated turbines [26].

A novel cavitation erosion device that produces vortex cavitation has been developed. The capacity of this formation of vortex cavitation to create real cavitation damage is compared to the same found in fluid equipment tested in a comparative study. In testing subjected to cavitation in water flow areas, hardened surface layers are identified to be denser compared to cavitation in vibratory conditions, leading to a greater amount of erosion [27].

The analysis of the variation, level of noise, and regularity bonding of the signals was done. The calculation findings were entered into a database and connected to the operational conditions provided by the head of water and the opening of the guide vane. Sound induced in flowing water and mechanical noise cannot be mistaken for the sound produced by cavitation because of its unique frequency characteristics. The head on the machine due to water flow and hydraulic power generated is used to determine the cavitation intensity. Due to the intensity of cavitation for a particular condition of operation, the actual power generated and planned with the water head is used to calculate the degree of cavitation erosion [27].

Hydroelectric power plants with different capacities are used to meet fluctuations in demand in electrical power networks. Hydraulic machinery was put through off-design operation in order to keep up with the rapidly changing market demands. There is a stimulating cause for the entire turbine setup in that whirling flow exiting the runner of a Francis turbine. Self-excitation occurred when a vortex rope was used under high-load operating settings because of its inherent energy source [28].

The deformation of the external provider cone in the bulb turbine is because of cavitation. At the time of the erection of the turbine, the top and bottom sides of the outer distributor cone inflate in size from the original dimensions. The left- and right-hand side dimensions were condensed from the erection data. The pressure waves and impact mechanisms are accountable for the impairment of the cavitation erosion phenomenon. Throughout his study, the author has found a correlation between the lie of the outer distributor cone and the number of hours worked in the equations.

6. Conclusion

According to the machine design and operating conditions, cavitation can appear in a variety of ways. Vibration levels rise, which leads to unstable machinery, deterioration of components, and downtime. Hydraulic turbines are particularly interested in the intake leading-edge cavitation, the bubble cavitation at the exit, and the swirling draught tube cavitation. These cavitation problems affect a wide range of hydro equipment. Cavitation has a noteworthy impact on

Kaplan Turbines, with output powers extending from 2 to 15 MW. Cavitation detection methods are normally taken up based on prior knowledge behavior of the cavity that creates the signals and their placement in the turbine housing that influences the propagation of the signals. In order to identify cavitation, detection methods depend on the monitoring of vibrations in the structure, audio discharges, and pressure of flowing water are selected. Vibrations on the runner blades are caused by unstable leading-edge cavitation, which propagates through the mechanical system. Vibrations in the supporting structure for turbine guide bearings are detected by measuring the runner. In general, vibrations in the radial direction are desirable to axial ones. Additionally, the guiding vanes are used to monitor noise levels. Detection of the draught tube wall is also commonplace to measure vibration and noise. In Kaplan turbines, the guide vane passing frequency has a high variation effect in inducing vibration. Depending on the degree of the cavitation, the magnitude of these frequency peaks changes.

Bulb turbines are designed for low head with high discharge axial flow (Kaplan turbine) hydraulic turbines, which is very much suitable for the situation in a barrage powerhouse where the net head is about 9m and the discharge is 271 m^3/sec.

At the blade passing frequency in the bulb turbine, the predominant modulations of the cavitation at the extreme ends of the runner blades are noticed. Radial vibrations in the guiding bearing of the turbine are watched to spot the same. Draft tube pressures are also supportive in getting the data; however, to get accurate values, wicket gate vibrations are suggested for this situation.

The amplitude of the whole spectrum rises as the cavitation damage increases, but the structure of the assembly does not change noticeably. For a finding of draught tube swirl, draft tube wall pressure observations are used to regulate the differences in pressure of the flowing water in the low-frequency area. The large amplitude vibrations spotted at the guiding bearing of a large Kaplan turbine have a variation frequency of a similar value.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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