How to Avoid Severe Incidents at Pumped Storage Power Plants

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Abstract. Pumped storage is now increasing its importance as the most powerful and reliable tool for stabilizing the electrical network, especially under the increase of intermittent power sources like wind-power and solar-power. However, pumped storage power plants have generally more machinery troubles than the conventional hydropower plants and sometimes they encountered unexpected severe incidents having long-term outage and a considerable restoration cost. The present paper provides some study results about general tendencies of machinery troubles in pumped storage, some examples of severe incidents mainly about the electro-mechanical troubles but also about the flood and fire, and possible scenarios which may lead into a severe result. Finally, it provides lessons learned and some recommendations to avoid severe incidents based on experiences.

1. Introduction

JPower, that has a formal name of Electric Power Development Co., Ltd, is the largest wholesale power company in Japan, having 8GW coal-thermal fleet and 8GW hydropower fleet. Especially, pumped storage power plants are the major component of hydropower fleet as indicated in Table-1.

| Plant Name               | Total Output(MW) | Units (No.x MW) | Commissioning Year | Remarks                                              |
|-------------------------|------------------|----------------|--------------------|------------------------------------------------------|
| Ikehara                 | 350              | 2x72+2x103     | 1964-1966          |                                                     |
| Nagano                  | 220              | 2x110          | 1968               |                                                     |
| Shin-toyone             | 1125             | 5x225          | 1972-1973          |                                                     |
| Numapara                | 675              | 3x225          | 1973               | World first 500m-class pumped-storage               |
| Oku-kiyotsu             | 1000             | 4x250          | 1978/1982          |                                                     |
| Shimogo                 | 1000             | 4x250          | 1988/1991          |                                                     |
| Oku-kiyotsu 2           | 600              | 2x300          | 1996               | Unit 2 is an adjustable-speed type                  |
| Kalayaan (Philippines)  | 720              | 2x180+2x180    | 1982/2004          | Jointly operated with Sumitomo Corp. from 2005      |
Those pumped storage power plants were generally constructed from 1960s to 1980s to meet the rapid expansion of Japanese economy. Due to the slowdown of new project developments in Japan after 1980s, JPower started the consulting services for the construction of pumped storage projects in Asia, especially in Korea, Taiwan, Thailand, India, and China. In a long history of pumped storage development by JPower, some severe failures occurred, including flood, fire and machine troubles. It is an objective of this paper to provide our experiences as good lessons to avoid any similar incident.

2. General tendencies of failures in pumped storage power plants

A pumped storage power plant, hereinafter it is abbreviated as PSP, has some specific characteristics comparing with the conventional hydropower plant.

- Many PSPs use the high-head, high revolving speed and large-output pump-turbines as the prime motor. The generator-motor is directly coupled with the pump-turbine, so it also has the high revolving speed, large-capacity and high-voltage. The mechanical stress level is generally higher than that of conventional machine.
- PSPs are operated with frequent start/stops due to many mode changes among pumping, generation, condenser operations. Those frequent start/stops generate low-cycle fatigue to the mechanical components and heat cycles to electric parts.
- Many PSPs use the reversible pump-turbines and generator-motors. The reversible pump-turbine runner has some specific characteristics to meet two functions of turbine and pump, so that the high vibration and high-cycle fatigue are to be inherent. The reversible generator-motor also has some weak points inherently in the rotor and bearing system.
- PSPs have complicated pump starting equipment and its associated electric circuits.
- Many powerhouses of PSPs are the underground type, so that the drainage system becomes a weak point due to the high pump head and large water seepage into the powerhouse.
- In case of the underground powerhouse, the main transformers are generally located in the underground cavern, which has risks of fire and explosion.
- Many PSPs are located in small river system, so that the natural flood is less probable. However, many valves and big pipes are provided around the pump-turbine, and their troubles sometimes cause unexpected flooding.
Figure 2 shows the probability of machine troubles per year and per one unit for each power plant type, which was obtained after analyzing 16,500 incidents, occurred at about 1,800 generating units in Japanese hydropower plants from 1995 to 2004 [1]. For an example, it indicates that each turbine in PSP has averagely a trouble once per 3-years by the ratio of 0.327. From the low probabilities, it is obvious that Japanese utilities are generally keeping their hydroelectric power plants in a good condition. It is also clear that the pumped storage type has double ratios of other types at the turbine, inlet valve, turbine control equipment, air compressor, generator and exciter.

Table-2 shows the distribution of comparatively serious incidents in JPower’s power plants in the last 12 years from 2004 to 2015, which caused mechanical breakdown and/or considerable outages more than 10 days. Table-2(a) shows the records of conventional power plants and its total incidents were thirty-six (36) by 52 plants having 85 units. The majorities of those incidents were caused by floods and degraded machines. The typical incidents are the clogging of intake and/or tailrace outlet with mud and debris, turbine troubles by jamming with foreign materials, oil leakage from packing, detachment of some parts by loosened bolts, etc. Table-2(b) shows the incidents at pumped storage power plants. It is obvious that the almost all troubles are derived from machinery failures of pump-turbine and generator-motor. The seven (7) domestic PSPs having 24 units had ten (10) incidents, but four units of Kalayaan PSP in Philippines had fourteen (14) incidents during the same periods. The latter had many troubles at the generator-motors and pump-turbines mainly due to the design and manufacturing defects.

![Figure 2. Probabilities of trouble for each power plant type](image-url)

**Table-2 Serious incidents in JPower’s Hydropower plants (Distribution ratio in percentage)**

| (a) Conventional Hydropower Plants | (b) Pumped Storage Power Plants |
|-----------------------------------|--------------------------------|
| **Civil facilities** | **Design/ Manufacturing** | **Maintenance/ Deterioration** | **Natural Disaster** | **Total** | **Design/ Manufacturing** | **Maintenance/ Deterioration** | **Natural Disaster** | **Total** |
| Civil facilities | 0.0 (0.0) | 8.3 (0.0) | 33.3 (0.0) | 41.7 (0.0) | 4.2 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 4.2 (0.0) |
| Turbine | 0.0 (0.0) | 19.4 (0.0) | 8.3 (0.0) | 27.8 (0.0) | 8.3 (0.0) | 25.0 (0.0) | 0.0 (0.0) | 20.8 (0.0) |
| Generator | 2.8 (10.0) | 8.3 (0.0) | 0.0 (0.0) | 11.1 (0.0) | 16.7 (10.0) | 4.2 (0.0) | 12.5 (0.0) | 41.7 (50.0) |
| Main Circuit | 2.8 (10.0) | 8.3 (0.0) | 0.0 (0.0) | 11.1 (0.0) | 42.0 (10.0) | 0.0 (0.0) | 0.0 (0.0) | 12.5 (20.0) |
| Station Service | 0.0 (0.0) | 5.6 (0.0) | 2.8 (0.0) | 8.3 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) |
| Control Eq. | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 8.3 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 8.3 (0.0) |
| Pump starting Eq. | - - - - - | 0.0 (0.0) | 12.5 (0.0) | 0.0 (0.0) | 12.5 (10.0) | 0.0 (0.0) | 0.0 (0.0) | 12.5 (10.0) |
| Others | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) | 0.0 (0.0) |
| Total | 5.6 (100.0) | 50.0 (100.0) | 44.4 (100.0) | 100.0 (100.0) | 37.5 (20.0) | 58.3 (70.0) | 4.2 (10.0) | 100.0 (100.0) |

Note: The incidents of the Kalayaan PSP are uncounted in the numbers put in the parenthesis.
3. Pump-turbine troubles

Some typical examples of severe incidents, which were experienced in the pumped storage power plants owned, operated or consulted by JPower, are shown as follows. In addition, some incidents occurred at the other utilities and reported publicly are also mentioned for your information. First of all, some incidents about pump-turbine are shown in the followings.

3.1. Runner cracks

High-head pump-turbine has a high stress level on the runner vanes, especially at the turbine leading edge near the junctions of runner vane with band or crown. In 1980s, when the 500m-class pump-turbines were put into practical use, some crack incidents occurred in Japan [2]. One cause of the crack was the high-cycle fatigue due to the resonance between the natural frequency of runner and the high dynamic loads by the Rotor-Stator-Interaction [3]. Another cause was the defects generated at the runner casting. To avoid the resonance, the tuning of runner natural frequency was conducted with the change of the runner periphery shapes. To reduce the defects, higher quality control was introduced at the runner manufacturing. Due to those improvements, the runner cracks became no more concern in 1990s. However, in 2007, two cracks were found at the leading edges of a pump-turbine runner in JPower’s PSP. Those cracks were caused by the inefficient post-heat-treatment after a welding repair of cavitation pitting in 2002. The high residual stress and degradation of metal properties at the HAZ (Heat Affected Zone) were concluded as the cause. The welding rod having similar property with the parent material: CA6NM of runner had been used for the repair, expecting the high strength, but the annealing was not enough to retrieve the original strength.

In 2008, some fatigue cracks were found in three pump-turbine runners in a PSP operated by JPower [4]. In the plant, those three runners were operated constantly with the very small output, nearly no-load, having high vibration level during four to six years after the installation. All cracks except for one crack were located at the turbine leading edge near the band, where the highest stress level is normally observed. The actual dynamic stresses of runner vane were measured at the site and it verified the crack generation. Another cause was the thin blade thickness, which is very popular for the modern runner design to achieve high efficiency. Those two cases are new types of runner cracks not anticipated in the past.

3.2. Detachment of some turbine parts

If any part would be detached from a runner itself or its surrounding stationary parts, it may damage the runner severely.

There were some examples of detachment of runner cone in some PSPs. One example occurred in the late of 1980s at a PSP in a Japanese utility, where the detached cone was uplifted under the pumping operation and crashed strongly with the runner. The detachment was caused by the fatigue of the connecting bolts. It is reported that a similar incident had occurred in a Chinese PSP in the late of 1990s, where the looseness of connection bolts caused a loss of the friction with the flange and bolts were sheared off [5]. JPower experienced similar example in a conventional hydropower plant and generally specified the welding work instead of the bolt connection.

The replaceable runner seal-ring is also prone to the detachment. It is reported that an American PSP had experienced the detachment of runner seal-ring in the late of 1970s [6]. As JPower experienced similar examples in some conventional hydropower plants, any high-head pump-turbine of JPower does not have the replaceable seal-ring at the runner.

In Japan, the split-type runner, which was divided into two or three pieces and assembled into a runner at the site, had been applied for many medium/low-head PSPs considering the difficulty of transportation in mountainous areas. In this runner type, the connecting flanges had to be covered with cover plates to smooth the runner outer surfaces. However, the detachment or crack generation of cover plates occurred in some Japanese PSPs in 1980s [7]. The cause was the self-excited vibration due to the vortexes generated at the inlets of balancing holes on the plate, consequently caused the
fatigue cracks. The addition of balancing holes to enable the flow circulation and the reinforcement of cover-plate were applied to solve the problem.

In 2008, nearly 200 cracks were found in a bottom ring liner at a PSP operated by JPower. The liner was attached to the bottom ring to provide the smooth water channel facing to the outer runner band. Fortunately there was no damage to the pump-turbine, but the liner was in a very dangerous condition. The cause was the fatigue corrosion by selecting improper stainless steel, but it was also suspected that the similar mechanism of self-excited vibration like runner cover plate might work for the generation of cyclic loads. The same PSP had experienced the severe runner damages by the detachment of bottom ring liner in 1990s, though the root cause of the incident was not verified definitely.

Figure 3 shows the possible scenarios of severe troubles at runner.

4. Generator-motor troubles
Generator-motor is the most prone to the severe damage in PSP as shown in the followings.

4.1. Rotor damages
The rotor had many troubles at the rotor pole, rotor coil, rotor coil wedge, rotor coil lead, dumper connecting terminal, etc.

It is reported that a PSP in Austria was severely damaged in 2009 [8]. A pole had been detached from the rotor after the trip by a lightning stroke to the transmission line, ruining the generator-motor and causing a fire. Although no definite cause of the incident is available, the crack generation by low-cycle fatigue at the rotor pole dovetails and/or rim is the most likely as the cause from some papers [8][9], which had shown the similar incidents at some PSPs in USA. Those problems occurred after a long-term operation with many start/stops, so that similar incidents are feared in the old pumped storage plants, especially when those plants are to be operated with far frequent start/stops in the de-regulated electric market.

Two incidents of rotor coil’s detachments occurred in China in the late of 2000s. It is reported that a generator-motor of a PSP had the considerable deformation of rotor coil [10], resulting the unbalance of rotor and the excessive run-out of shaft system. Another case had severe damages at the simultaneous load-shutdown test of two generator-motors due to the detachment of rotor coils from poles [11]. Both incidents seemed to be derived from the defective design of the rotor pole.

In 2007, a PSP of a Japanese utility had experienced an excessive run-out of the shaft system due to the breakdown of upper guide bearing [12]. In the case, a blackout caused the loss of lubricating oil
film and excessive force was concentrated at an adjusting bolt of a metal pad. The buckled bolt made the gap wider, so that it caused instability of rotating parts. In 2009, another unit of the same PSP suffered the excessive deformation of the rotor coils [12]. The latter was caused by the improper manufacturing process of the windings.

In 2009, a PSP operated by JPower had experienced a detachment of rotor coil wedge, which was provided to prevent the excessive deformation of rotor coils. In that case, the detached wedge was trapped in the gap between the rotor and stator, consequently damaged the stator core severely. The cause was the weakness of insulation plate inserted between the rotor coil and the wedge. The broken plate contacted with the stator and caused the detachment of the wedge by its high vibration. It took nine months to recover from the incident due to the partial core replacement.

The connectors between the rotor poles, connectors of dumper windings and the rotor leads to the slip ring are also prone to the detachment. In 2010, a PSP of JPower suffered a damage of stator caused by a detached connector from dumper windings. Any detached part from a rotor may damage a stator severely, but also a loss of excitation at some poles may cause an excessive run-out.

In 2006, a PSP operated by JPower experienced whole circumferential cracks [4] at the lower spider disks of two rotors, which were caused by the excessive vibration having the resonance with natural torsional frequency of the rotor and by the stress concentrations at the sharp corners.

Figure 4 shows the possible scenarios of severe troubles at rotor.

4.2. Stator damages

Stator may also have some severe damages. In 2010, a PSP of JPower had a grounding fault of a stator coil by the damage of coil insulation. The coil was placed in a slot located at the connection of two core blocks. Emergency inspection revealed that another block’s connection had overheating with melting debris. This stator has been constructed from eight pre-assembled core blocks, but the long-term heat-cycle caused galling at the connecting surface and the eddy-current caused overheating. The stator was temporarily repaired, but it was finally replaced into a new one to make sure the long-term reliability.
In 1989, another JPower’s PSP had an incident, in which a connector connecting one of two parallel circuits of phase V to the neutral point was broken down and remained circuit was overheated with the over-current, subsequently high temperature damaged over various parts such as the phase W windings of stator, rotor coils, thrust bearings and generator housing. The cause of broken connector was the loss of tightening torque of bolts due to the long-term use with heat-cycle and vibration. In addition, there were some incidents in which the detached parts such as broken core piece or core compression plate from stator damaged the stator or rotor in the JPower’s conventional hydropower plants. Heat-cycle, vibration, overheating and looseness of bolts are to be possible causes. Although we have no example, there is a risk of generator fire, especially when the protection is not so reliable due to DC power loss, fault at blind spot, mal-setting of relay, etc. The old stator coils using non-epoxy-resin insulation system has higher risk. Figure 5 shows the possible scenarios of severe troubles at stator.

5. Fire incidents
In 1980, a JPower’s PSP had a fire in the station service power room since a circuit breaker of pony motor had failed to open the circuit due to a looseness of connecting bolt of a conductor. The fire was expanded to the cables running over the circuit breaker cubicle and caused a whole loss of AC and DC power in the power plant. A generator-motor was operating in a pumping mode at the fire and the loss of DC power caused a continuous motoring without any cooling capability since cooling fans and water supply pumps had stopped, so that the temperature of generator-motor had reached to the dangerous point. The maintenance staffs entered into the smoke-filled plant with the breathing device equipped, and managed to stop the machine by closing the inlet valve and tripping the main circuit breaker. This incident provided us many lessons to be learned including the need of back-up system of DC power and the importance of fire drill.

In 2006, a PSP operated by JPower had experienced a small fire just under the supervisory control room. The cause was the degraded power cable of air-conditioner and its over-heat by the wrong connection work. It is reported that similar incidents had occurred at two hydropower plants in USA in 2002 and 2012 [13][14], one had a fire in the cable shaft and another had a fire at the cable rack under the control room. All three cases indicate that the degraded old cables become the source of a fire. High-voltage oil-filled (OF) cable is also dangerous to a fire incident. Although we had no example in any PSP, a conventional hydropower plant in Indonesia had two fire incidents at the junction boxes of 275 kV OF cables in 1995 and in 2000. The heat-cycle of cable was assumed as the main cause, which generated a stress concentration at the cable termination portions. Fires of OF cables were also reported in some hydroelectric power plants [15][16].

In 1992, a PSP in Taiwan had an explosion of a main transformer in the underground transformer cavern. The blast attacked the main cavern and blown off a heavy hatch in the air, causing one fatality, a JPower’s engineer, and three severe injuries. The cause was a lightning which struck a transmission line tower nearest the plant and low resistance of the transformer for lightning surge.
incident, we generally consider to provide additional surge arrestors nearby the transformer as a failsafe purpose when the transformer is installed in underground cavern at overseas projects. Figure 6 shows the possible scenarios of fire in PSP.

6. Flood incidents

In 2008, a PSP operated by JPower had a flood incident caused by the valve troubles due to a blackout [17]. This incident had been mainly caused by the accidental opening of three drain valves at the cooling water supply strainers, which connected the draft tube directly to the drainage pit of powerhouse, and by a short-circuit failure of one drainage pump at the retrieval of electricity. It took one year to restore the plant from the incident, but two stators were finally replaced with new ones after the restoration works of flood due to the degraded stator coils.

In 2005, a PSP in India, which was under the construction, had experienced a landslide by heavy rain from the upstream area of the lower reservoir. The mud flow entered the tailrace tunnel after overcoming a temporary bulk-head at the inlet. Fifteen workers were killed in the tailrace tunnel and the underground powerhouse was submerged under muddy water.

In 2005, an underground powerhouse of JPower’s conventional plant had a short-circuit failure at the station service transformer due to the rushed water from the access tunnel. The cause was the clogging of drain gutters at the tunnel entrance by debris. Underground powerhouse is prone to the flooding. Figure 7 shows the possible scenarios of flood in PSP.

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**Figure 6.** Possible scenarios of fire in PSP.

**Figure 7.** Possible scenarios of flood in PSP.
7. Lessons learned and some recommendations

For the machinery failures, a concept of life-cycle maintenance as shown in Figure 8 is one of the practical approaches to study the preventive measures and actions since the causes, features and failed parts of many severe machinery failures are strongly related with the operating time.

Until about five years later the commissioning, many initial failures may occur due to defects at design, manufacturing and installation stages. The typical initial failures are the high-cycle fatigue at the runner and rotor, bolt looseness at flanges and connecting terminals, excessive deformation of rotor coils, breakdown of guide bearings, etc. Sometimes the stable operation would be difficult by the pump-turbine instabilities like power swing and S-curve characteristics. Therefore, it is recommended to check the machine’s healthiness and integrity thoroughly at the commissioning tests and to make the first intensified inspection of vulnerable parts in this period. If any severe incident would happen unfortunately, the root cause analysis should be completely done to avoid any recurrence. When some cracks had been found in runner vanes, we made a field measurement of dynamic stress level. Although it took a considerable cost, the confirmation of repaired runner’s healthiness justified it [4].

During a period from five to twenty years after the commissioning, the plant is generally in a calm state since almost all initial failures had been rectified and the maintenance staffs are familiar to the machines. During the period, the main problems are the cavitation pitting of the runner vanes and sporadic breakdown of various parts. The first overhaul is conducted during the period for the repair of cavitation, replacement of worn-out parts and comprehensive inspections of critical parts. When the cavitation occurs at the turbine leading edges of high-head pump-turbine, the repair has some difficulty due to the high stress level and it is necessary to make a careful study for the repair.

During a period from twenty to thirty or forty years after the commissioning, the initial degradation becomes obvious in the stator coil and runner. It is recommended to conduct overhaul works to repair or replace the damaged parts before the severe incident happens. At that time, some vulnerable parts to the possible severe incidents should be checked thoroughly, including rotor poles, rotor coils, connecting terminals of rotor/damper coils, runner and its surrounding accessories, coupling bolts, etc. The short-lived computer-based equipment has to be replaced into new one to ensure the reliability.

About thirty to forty years later the commissioning, a low-cycle fatigue may be generated at the rotor pole, stator, bearing brackets and other various parts. Degradation of insulation system of electrical equipment may become obvious in this period. The renewal or comprehensive repair of some main components such as stator, rotor, runner and M.Tr are to be considered in the major overhaul.

Note: The durations of periods and time schedules of overhauls would be dependent on the actual conditions of the machine and the owner’s policies.

Figure 8. Life-cycle maintenance of Eq. in PSP
Fire is the most critical incident both in lives and property damage. It is recommended to make periodical inspections of degraded cables, old switchgears and oil-immersed equipment. Fire alarms should be located adequately to detect an incipient fire and fire drill should be effective to meet any accidental occurrence. Hydroelectric powerhouse easily becomes a confined space under a fire, so that the escape route should be ensured, especially at the lower floors.

For a flood incident, it is recommended to make periodical checks of possible dangerous valves like the air vent valves, drain valves and others, which may directly and accidently connect the draft tube to drainage pit under some failures. If possible, it is safer to provide back-up valves. The control function of those dangerous valves should be ensured even under the failure of AC and DC power supply. A jet pump is reliable to keep the drainage capability at a blackout. Periodical inspection of drainage pumps and its control equipment are also indispensable. The motor control center of drainage pumps should be located in a higher floor and water level gauge should be water-proof type.

It is impossible to make all machines immune from any accidental failure, so that it should be studied how to restrict the damage as small as possible. The most promised way is to keep the protection relays as much as reliable and to provide some backup system to make sure the successful emergency stop. JPower normally provides backup control circuits to trip the generator circuit breaker and to close guide vanes and inlet valve. The past failures will provide many lessons learned to prevent similar incident, so please utilize this paper for ensuring the steady and safe operation of your plants.

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