Lessons from the accident at the Sayano-Shuskenaya hydropower station

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EEA Conference & Exhibition 2010, 17-18 June 2010, Christchurch

Abstract

At 08:13 local time on 17 August 2009, the 6400 MWSayano-Shuskenaya 170 m head hydropower station on the Yenisei river in Siberia was flooded and 75 lives were lost.

It transpired that Unit 2 had suffered a catastrophic failure of the bolts holding the turbine cover to the stay ring. This resulted in the ejection of the turbine and the generator rotor, a total weight of about 1600 tons, from the pit. Units 7 and 9 also suffered severe damage from being flooded while rotating. The roof of the turbine room collapsed and damaged turbines 3, 4 and 5.

The penstock guard gate failed to close automatically and, as a result, the station was completely flooded. It is likely that this caused most of the fatalities. Because there was a complete power failure, it took more than 24 hours to open the spillway gates. By then the dam was dangerously close to overtopping.

The paper will discuss the accident itself, the causes of the accident and point out that the failure appears to be very similar to the failure at a hydropower station in Canada about 20 years ago. The author has in-depth knowledge of that failure as he was an expert witness for one of the parties in the ensuing litigation.

In both cases, the unit was frequently operated outside safe operating ranges, maintenance was inadequate and early warning signs were ignored.

The paper also discusses the wider implications of the failure and, in particular, the dangers of long term metal fatigue, the need for reliable safety systems and the need for spillway gates to have two independent operating systems, one of which will operate in the absence of an external power supply and without manual intervention. The paper points out that there are few stations anywhere in the world that meet all these requirements.

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Thu, Nov 12, 2009

Introduction

At 08:13 local time on 17 August 2009, the 6400 MWSayano-Shuskenaya 170 m head station on the Yenisei river in Siberia was flooded and 75 lives were lost.

It transpired that Unit 2 had suffered a catastrophic failure of the bolts holding the turbine cover to the stay ring. This resulted in the ejection of the turbine and the generator rotor, a total weight of about 1600 tons, from the pit. Units 7 and 9 also suffered severe damage from being flooded while rotating. The turbine room roof collapsed and damaged turbines 3, 4 and 5. Unit 6, which was being repaired at the time, received only minor damage.

What follows is based primarily on a presentation entitled "Reflections on Russian accident on August 17, 2009" by Eugenio Kolesnikov[1] that, in turn, was based on a report released in Russian on 3 October 2009[2]. I have also added information from other websites and from a widely circulated presentation dated 24 Aug 2009[3]. The 3 Oct report is sufficient to build up a scenario that adequately explains what happened and why it happened. This does not rule out the possibility that more evidence and alternative explanations will be revealed in the future.

The conclusions I have drawn are based on my assessment of the evidence and my close association with a very similar failure that occurred in a North American power plant a few years ago.

The station

The station has 10 x 640 MW units producing 24,000 GWh a year (42% capacity factor). The first unit went into in operation in December 1978 and the 10th unit was operation in December 1985. The plant was officially commissioned in 2000. Major overhaul and control system upgrades started in 2005 and were planned to extend until 2011.

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1 This report is available on my website www.bryanleyland.co.nz under publications/hydropower. The figures are from this report. The report goes into much more detail on the failure and what caused it.

2 On 3 October, the results of investigation of the accident were announced by the Federal Environmental, Technological and Atomic Supervisory Service (Rostekhnadzor) in a press conference with its head, Vladimir Kutin. (Wikipedia)

3 Euler Cruz Consulting Engineer – Turbines and Rafael Cesário Mechanical Engineer (Brasil)

Figure 1 Dam and 6400 MW power station

Sequence of events leading to the failure

There was fire in a communication room at the nearby Bratskaya hydro plant. As a result, Sayano-Shushenskaya was instructed to manage system frequency. Unit 2 was selected as lead turbine for automatic frequency control. Unit 2 was showing a high level of vibration even though it had recently been overhauled.

The system frequency controller unit was new and, possibly, not properly tuned and tested. It had a tendency to "over regulate" and hence Unit 2 was subjected to large load swings. Some load swings took the turbine into its mid range band where vibration became severe. The unit was not supposed to operate in this band. Just before the failure, the controller was driving the unit in and out of this band at frequent intervals.

It appears that, although vibration was monitored, a high vibration trip was either not provided for or was not armed. Records of vibration show that the vibration level exceeded the recommended level around the end of June and rose steadily until a few days before the accident when it was about twice the recommended level. From then on, vibration levels rose rapidly until the final failure.

Sequence of events during and after the failure

The high vibration induced fatigue cracking in the turbine cover bolts. In the final moments they broke off in sequence until they could no longer contain the pressure under the turbine cover. At this point, the remaining bolts broke simultaneously. The water pressure beneath the turbine was sufficient to hurl the turbine cover - which carried the generator thrust and guide bearings - and the generator rotor into the air. The turbine cover was a reasonably neat fit in the turbine pit and, in effect, the turbine pit became the cylinder of a huge hydraulic ram

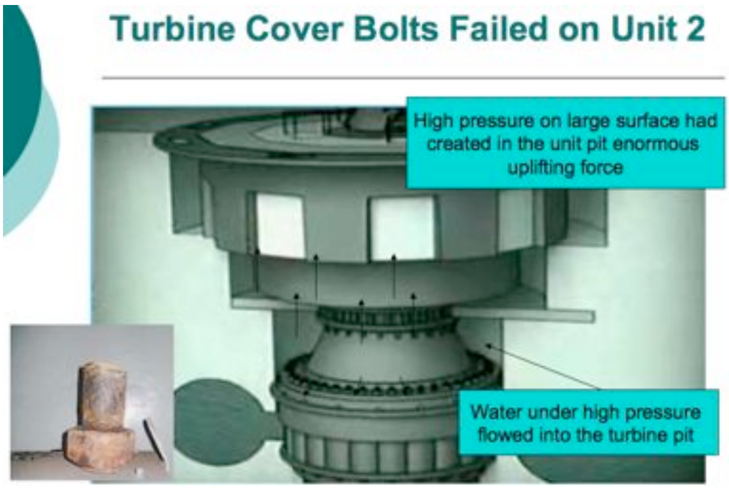

Figure 2 Turbine and generator assembly

and the whole area of the turbine cover became the piston.

Sufficient force was generated to hurl the still rotating turbine and generator rotor something like 14 m into the air. The total weight was in excess of 1500 tonnes. Because of the gyroscopic effect, the spinning mass descended back into the turbine generator pit. The rotor then disintegrated and the remains of the rotor spider became wrapped around the generator shaft.

Figure 3 Unit 2 Generator rotor and turbine spinning above the generator floor level

All this time, vast quantities of water were jetting into the powerhouse. The head gate should have closed automatically but it did not. This may have been because some parts of the trip mechanism were faulty or because the destruction in the powerhouse destroyed the trip devices before they had time to operate. One or more operators climbed up the internal stairs in the dam from the power station level to the top of the dam and finally closed the head gate manually about an hour after the failure.

Figure 4 Unit 2 turbine and rotor spider

Very soon after the failure, the powerhouse was flooded to close to the loading bay level. Unit 2 was totally destroyed and Units 1 and 3 were badly damaged from flying debris from Unit 2. Unit 7 and 9 generators were flooded while they were still rotating and the hydraulic pumping forces between the rotor and the generator destroyed the stators. A large section of the powerhouse, that was of space frame construction, was totally destroyed.

There seems to be little doubt that if the head gate had closed automatically when the accident occurred, the damage would have been much less and many of the people in the powerhouse would have survived.

Because the station was no longer passing water downstream, it was imperative that the 10 spillway gates be opened as soon as possible. Because there was a complete power failure in and around the station, there was no power to operate the single gantry crane that was used to lift the spillway gates[4]. The gantry crane did not have its own emergency generator. After some time, a suitable emergency generator was located and connected to the gantry crane. Two days after the accident, the spillway gates were open.

The report implies that the dam would have overtopped two or three days after the accident if the spillway gates had not been opened. If the dam had overtopped, it would have destroyed what remained of the powerhouse and may have caused a catastrophic dam failure.[5]

There is still one remaining risk. All the flow of the river is now passing through the spillway gates and the energy is being dissipated in the stilling basin at the foot of the spillway. In the past, there has been severe erosion in the stilling basin and very large amounts of concrete were needed to repair the damage. If it is forced to operate continuously for a year or two, it is possible that the stilling basin will be severely damaged. However, an auxiliary spillway is under construction on the right bank. If it is completed in time, it will allow the existing spillway to be shut down for inspection and repair.

The cause of the failure

The probable cause of the failure was excessive vibration causing long term fatigue of the bolts holding the turbine cover to the stayring. According to the 3rd October report, many of the bolts had major fatigue cracks. Some, it seems, had their nuts missing completely. Inspection of the bolts after the accident revealed that several of them had cracked right through from long-term metal fatigue at some time before the accident.

The turbine cover carried the turbine and generator guide bearings and the generator thrust bearing. This meant that the whole load of the turbine and generator was carried down through the stayring and into the powerstation foundations. Under normal operating conditions, it seems that the thrust from the water exceeded the total weight of the generator and turbine hence the bolts were normally in tension (in addition to the tension caused by the tightening of the bolts). The tension in the bolts would vary during load changing operations, particularly stop/starts and would also be affected by machine vibration. If excessive, this can lead to fatigue. The fact that the bolts were quite short and may have been subject to stress corrosion, added to the risk.

It seems that unit 2 had always vibrated more than any of the other machines in the station. After the recent overhaul, the vibration was still several times higher than it should have been.

It is reasonable to conclude that the steady increase in levels of vibration experienced in the period before the accident was the result of more and more bolts cracking, and in some cases, failing completely.

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[4] Instead of having lifting gear associated with each spillway gate, a single gantry crane moved from gate to gate opening them one by one.

[5] Once the dam overtopped it would have been difficult or impossible to open the spillway gates. As there has been a history of foundation problems at the dam it is possible that the overtopping coTheuld have eroded the foundations resulting in dam failure.

Similarity with a failure at a North American power station
About 15 years ago, a power station in North America was flooded as result of the failure of headcover bolts that had suffered from long-term metal fatigue. Investigations showed that some of the bolts had cracked off completely some time before the failure and many others were more or less severely cracked.

There were varying opinions on what caused the cracking. Probably the most credible explanation was that, as at Sayano-Shushenskaya, the unit was under the control of an automatic system for managing system frequency. The control system over-corrected and, as a result the output of the machine often decreased to zero. Every time the guide vanes closed completely the turbine cover bolts experienced a stress cycle no different from that experienced during normal starting and stopping. Stress calculations indicated that several thousand start/stop cycles were needed to have caused the observed fatigue cracking and it was highly likely that, because of the actions of the frequency controller, sufficient cycles had accumulated.

At the North American station the head gate closed very shortly after the accident and this limited the flooding of station. Fortunately, there was no loss of life.

The lessons from the failures

Failure of the turbine cover bolts
A common factor in both failures was that imperfect controllers forced the turbines to work over a wide range of loads at frequent intervals. In both cases, these load ranges extended into regions where it was not prudent to operate the units.

Since deregulation and the advent of electricity markets, control of generation in many jurisdictions has switched from the system and powerstation operators who, in general, had a good understanding of power systems, the capabilities and limitations of the generating plant and the daily fluctuations in demand that were likely to be experienced, to traders who see generating plant primarily as a way of maximising profits in the market. To maximize profits, it is often necessary for stations to change power output at frequent intervals.

Another problem in many electricity markets is that the supply of "ancillary services" such as frequency management, spinning reserve and synchronous condenser operation is determined on an arbitrary basis or depending on the prices bid in by various generators at various times. This means that it is no longer possible to make sure that the machines that are best suited to provide frequency management are selected to do this and that frequency management is shared amongst several power stations. Hence units that are selected for frequency management may well be forced to operate over load ranges that have the potential to cause serious damage.

Another factor with the potential to cause damage is the advent of windpower which makes it much more difficult for the system operator to schedule conventional plant to meet the expected load. As well as coping with rapid and unpredictable fluctuations in output, the system operator has to assume that the wind output could drop very substantially within a short timescale and, as a result it is necessary to have power stations operating at a low output to make sure that a sudden drop in windpower will not cause a "brownout".

The conclusion is, that more than ever, many hydropower stations are operating in conditions that put them at risk of failures similar to the two discussed above.

So the first lesson from the failures is that all owners of hydropower stations should be very much aware of the risk of fatigue cracking and failure of headcover bolts, stay vanes and other vital components subject to fluctuating stresses. If, as a result of new operational requirements, the units are operating with more load changes than previously and are often in undesirable operating ranges, a past history of freedom from fatigue cracking should not be assumed to guarantee freedom from cracking in the future.

An associated lesson is the need to monitor vibrations and the absolute requirement to have a vibration monitoring device that will trip the unit if vibration becomes excessive. Note that this does not necessarily require an expensive and complicated vibration monitoring system. For smaller turbines, a simple magnetically latched vibration device maybe all that is required.

Failure of the head gate to close immediately

In New Zealand at least, it is standard practice to have a head gate that will close automatically on receipt of a signal from the station and also in the event of excess velocity in the penstock. It is also standard practice that the head gates should close very rapidly - periods of 30 seconds to 1 minute are achieved even in stations where the turbine flow is well in excess of 100 m3/s. In other countries, for reasons that I do not understand, much slower closing speeds are employed. For fast closing speeds, it is important is to have an adequately sized air vent downstream of the gate and, if the gate is very large, it is a good idea to have a "cushioning" stroke so that the gate slows down before it finally closes.

At many power stations, it is still normal practice to rely on the operators to close the head gate in an emergency. At other stations, in gates are held open by devices the can only be released if the gate is first lifted by the intake gantry crane. As the failure at Sayano-Shushenskaya proved, this is no longer acceptable. Basic risk management requires that intake gates close automatically and reliably when needed[6].

Opening of the spillway gates

The accident highlighted the risks of having spillway gates opened by a single lifting device shared between all the gates. This means that a failure of a single lifting device or its power supply immediately creates a hazardous situation that could lead to dam failure.

As I explained in a recent paper[7], I believe that every spillway gate should have two independent means of opening the gate with at least one of them operating without human intervention and without an external supply of power.

Conclusion

No-one in the hydropower industry worldwide should assume that "it could not happen to us". It is virtually certain but there are many stations at risk of a similar failure. At some of

[6] "Operational performance and safety requirements for Hydro-mechanical equipment", Magno et al, hydropower and dams, Issue 5, 2009

[7] "A new system for raising spillway gates" Leyland B, Hydropower and Dams, Issue 3 2008

these stations, such a failure could lead to a situation when the spillway gates fail to open, the dam overtops and, possibly fails.

When we build a large dam, we create something that is potentially extremely dangerous and that needs constant monitoring and maintenance into the foreseeable future[8]. The hydropower industry must recognize that this is the case, and make sure that large dams and their powerstations are designed, constructed, monitored and maintained to a very high standard.

These two failures show that every owner or operator of large hydropower stations needs to be confident that turbine cover bolts, stay vanes etc are inspected and crack tested; that inlet gates or turbine guard valves will close automatically when needed and that spillway gates can be relied on to operate without human intervention and without an external power supply.

"The price of safety is eternal vigilance".

[8] "Large Dams - Implications of Immortality" Leyland B, International Water Power and Dam Construction, 42(2) 34-37, 1990