

Transient problems upon load rejection

Masjed-e Soleyman case study

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Introduction

Masjed-e Soleyman has 4 Francis units with $D = 4.286$ m, commissioned in 2002 and 2003. Full power with one unit is 254 MW under 147 mWC. An extension with four more similar units is under construction.

Units 3 and 4 on the right waterway (looking downstream) share a common penstock and a common long tailrace tunnel. Units 1 and 2 on the left also share a penstock and tailrace tunnel. Downstream surge tanks were considered in the early stages, but were not incorporated in the final design due to geological problems leading to very high costs.

Normal operation is smooth. Full load operation is completely quiet. Part load fluctuations are not excessive. Air admission during steady-state operation is not necessary.

Upon commissioning of unit 4, the hydraulic transient in the draft tube during load rejection above 75% was excessive. It was apparent that the guide vane closing law that had been adopted would result in water column separation during load rejection at full power. Tests with a slower closing rate showed that the risk of column separation was reduced, but a violent surge developed in the draft tube close to maximum overspeed. A slower closing stroke was not possible because it would cause a speed rise above the design overspeed of the generator.

Adjustments of the guide vane closing law established a law that was acceptable for the emergency shutdown of one unit. However, with this law, the maximum allowable power output of the pair of units on one waterway had to be restricted. Obviously, this carried a very high economic penalty.

To see if a solution to this problem could be found, the Iran Water & Power resources development Co (IWPC) appointed the authors to identify the causes of the pressure surges and to make suggestions to solve the problem.

The paper describes the panel’s analysis of the surging, the method of surge mitigation by air admission, conceptual aspects of the air admission system and comments on alternative solutions.

1. Background

Masjed-e Soleyman (MES), also called Godar Landar, is a dam and power plant on the Karun River, in the foothills of the Zagros Mountains near the City of Masjed-e Soleyman, Khūzestān province, I.R. Iran. MES is designed to supply peaking power to the Iranian grid.

The underground power plant is being built in two phases. Phase 1 consists of two waterways, each feeding two units. The four units of phase 1 were commissioned in 2002 and 2003. Phase 2 will have two more waterways and four units in an extension of the phase 1 cavern.

Figure 1 shows the main power plant data and the layout of the waterways for phase 1. The penstocks drop directly from the intakes to the powerhouse and divide to feed two turbines each. Each pair of draft tubes joins into a long tailrace tunnel leading to the outlet at the foot of the dam.

MES was initially planned with downstream surge tanks [1]. During construction, the quality of the rock in the surge tank area was found to be very poor so it was decided not to build the surge tanks. To compensate, the tailrace tunnel diameter was increased to 11 m.

Number of units	4 (phase 1) + 4 (extension)	Penstock diameter	9.5 m	
Full power (1 unit)	254 MW	Tailrace tunnel diameter	11 m	
Runner diameter	4.286 m	Waterways	Units 1-2	Units 3-4
Rotational speed	187.5 rpm	Penstock length, phase 1	283 m	329 m
Best efficiency point	145 mWC, 170 m ³ /s	Tailrace tunnel length	440 m	470 m
Main Thoma number σ	0.170	Specific speed full power	$n_{QE} = 0.183$ ($ns = 212.4$)	

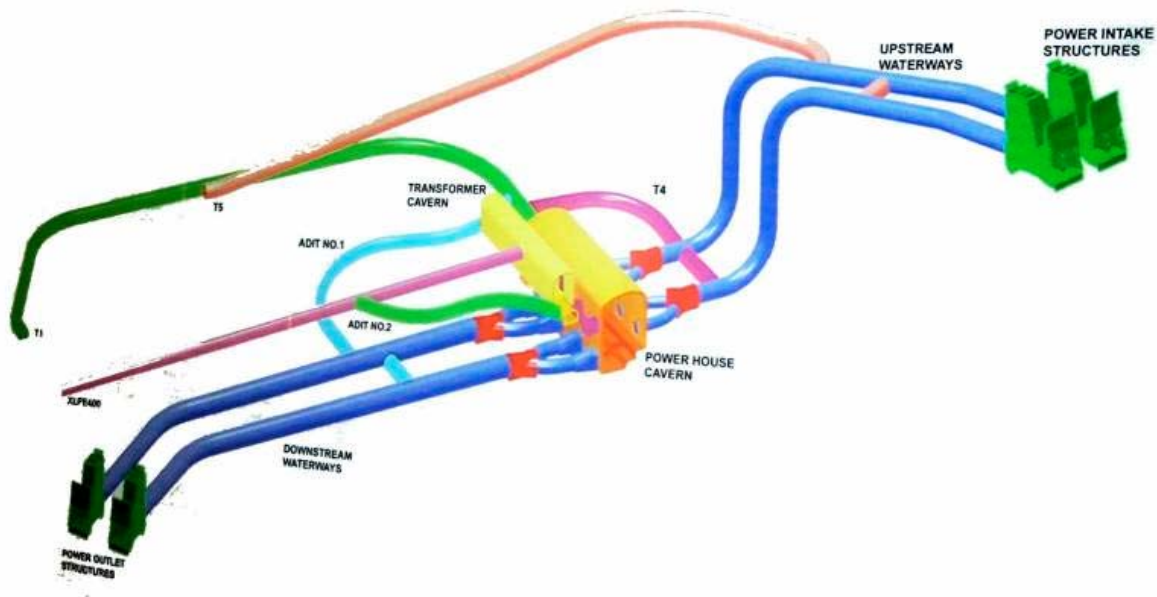


Fig. 1. Masjed-e-Soleyman main data and phase 1 waterways

2. Problems during load rejection

2.1 Load rejection tests

Load rejection tests¹ are among the important tests during commissioning. The ability of each unit to withstand the exceptional conditions of emergency shutdown or load rejection must be tested before operating of the unit on commercial load. The tests are normally done in several steps up to the maximum power. When, as in MES, two units are on the same waterways, the load rejection tests must be done individually on each unit then repeated with the two units.

When the generator is disconnected from its load, the rotational speed increases due to the hydraulic torque on the turbine. The governor senses the higher speed and causes the turbine distributor to close rapidly to prevent

¹ Load rejection and emergency shutdown tests are distinct. For the purposes of this case study, only load rejection is discussed. Emergency shutdown causes the same phenomena.

the rotational speed from reaching excessive values. The rapid closure of the distributor causes the spiral case pressure to rise and the draft tube pressure to drop as a result of water hammer effects.

The rotational speed must not exceed the maximum value allowed by the contract. For the MES turbines, the maximum allowed overspeed was initially 152%.

The risks during load rejection are excessive pressure in the penstock, an excessive pressure drop in the draft tube and an excessive rotational speed inducing shaft vibrations and loss of bearing oil. In the case of MES, the penstock pressure was not a problem but draft tube pressure drop and speed rise were excessive.

2.2 Attempts to optimize the closing law, draft tube surge

During testing of the first unit in September 2002, the draft tube pressure drop was found to be excessive for loads greater than 75% [1]. In most cases, a suitable compromise between speed rise and draft tube pressure drop is obtained by adjusting the distributor closing law. It is common to introduce a break point (see figure 2) with rapid closing at first to minimize the speed rise, then slower closing to minimize the pressure drop.

Water hammer calculations were done to see if better break point and closing rates could be found. They indicated that load rejection at full power could be safe with a slower first closing stroke and a lower break point. Tests with the new settings caused a sharp pressure surge in the draft tube, see figure 2. This surge propagated to the spiral case and penstock and caused big dynamic loads on the mechanical assemblies of the turbines and on the anchoring of turbine and piping elements in the concrete. It could be due to a sudden collapse of the draft tube vortex cavity or to a burst of self-excited instability [3] at the particular unsteady operating conditions of the unit at 50% of best efficiency energy coefficient, 30% of best efficiency discharge coefficient, and low Thoma number. Either of these would explain why water hammer calculations failed to predict the surge, as conventional water hammer calculations are limited to one-dimensional hydro-elastic effects in pipes filled with homogeneous, isotropic fluid.

Figure 2 shows a severe surge during an emergency shutdown with one unit. This test showed that the trial and error method of break point adjustment, even supported by water hammer calculations, was too dangerous to continue with. Another way of producing a satisfactory solution had to be found.

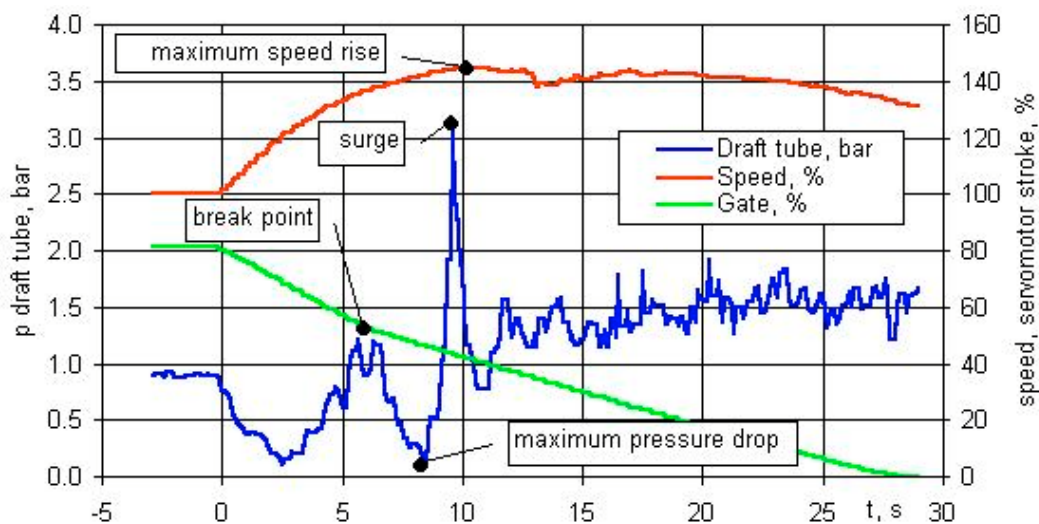


Fig. 2. Main features of load rejection

3. Air admission

3.1 Purpose of air admission

Air admission was proposed [4] as a method of damping or suppressing the surge. It was estimated that an air quantity of about 80 Nm³ from a 12.5 m³ vessel inflated to 35 bar could be sufficient for mitigating the surge for two units.

For comparison, this volume, to be injected in 15 s from the start of distributor closure, is roughly equivalent to 50% of D³ for each unit. Another comparison would be to express the air flow at atmospheric pressure as 1.7 % of best efficiency discharge averaged over the time of air admission.

These air quantities are smaller than those usually required to stabilize a part load instability [3]. It was expected that the air volume would modify the vapor dynamics sufficiently to eliminate the self-excited surge, or that it would create a small air cushion that would prevent the collapse of the draft tube vortex cavity. This would reduce the surge enough to make the full power load rejection safe.

This use of air admission for this purpose is not conventional. We could find only one reference, not documented, of a similar strategy in 1989 on the 134 MW turbines of the Uri power plant in India.

3.2 Load rejection tests of June 2003 with air admission

Air admission equipment was installed on one unit and tested in June 2003 [4]. The air piping was not built as required, and so the available air flow was only $1.2 \text{ Nm}^3/\text{s}$ on average over the first 4 s, i.e. only 0.7% of the best efficiency discharge. The air was injected both in the headcover and through a series of holes in the draft tube ring below the runner band (figure 3).

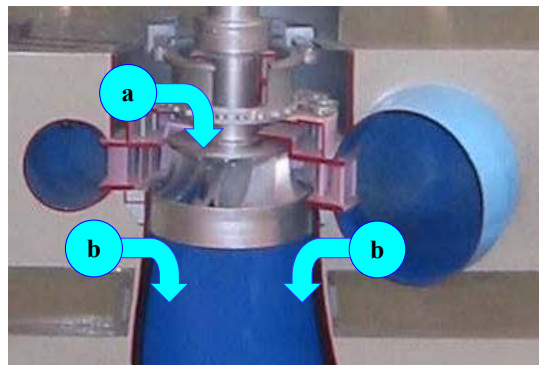


Fig. 3. Air admission in the headcover (a) and through the draft tube ring (b)

Load rejection was tested at 75%, then 100% of full power, as shown in figure 4. The reduction of the surge amplitude was not spectacular, but significant. The surge was not a sharp shock anymore, and propagation to the penstock was reduced. It was concluded that air admission in combination with an optimized closing law could solve the problem.

One adverse effect of the air admission was a 2% increase of the maximum speed rise. This may seem logical at first glance, but is actually not easy to explain.

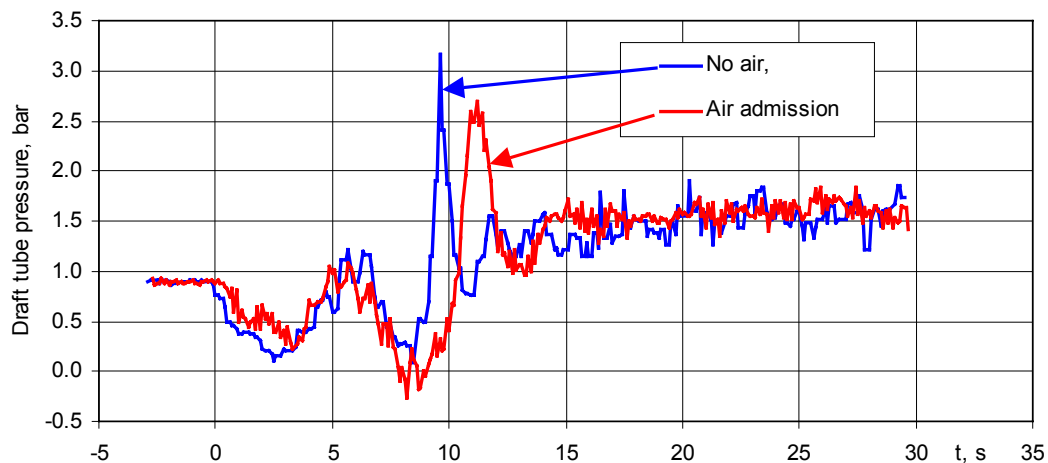


Fig. 4. Full power load rejection with air admission, one unit, June 2003

3.3 Load rejection tests of November 2003 with air admission

The air admission system was improved and the “panel of experts” mission came to the project site in November 2003 to assess and improve the effectiveness of air admission in mitigating the problems encountered in the load rejection of the MES turbines [2].

With the improved air admission system, the air discharge was increased to $2.6 \text{ Nm}^3/\text{s}$ on average over the first 10 s of air admission.

It was observed that injecting air through the draft tube ring (b, figure 3) was not efficient. Much of this air is entrained by the high water velocity at the band, and is not effective in inflating the vortex cavity or in cushioning a cavity collapse. On the contrary, air injected in the headcover (a, figure 3) goes to the draft tube through the pressure balancing holes and stays below the runner. At partial distributor openings, the discharge velocity is lower in the central region of the draft tube.

Figure 5 shows the complete elimination of the draft tube pressure peak upon load rejection with the increased air quantity and with injection in the headcover only. The maximum speed rise increased as it did in the June 2003 tests.

The elimination of the draft tube pressure recovery transient 3 to 8 s after the start of load rejection shows that the larger air quantity completely modified the dynamic response of the water column in the tailrace tunnel during load rejection.

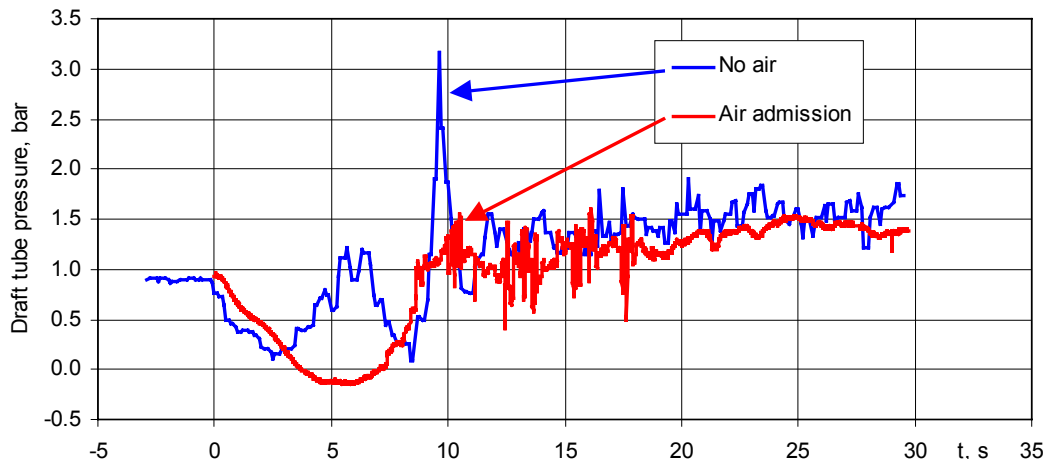


Fig. 5. Full power load rejection with air admission, one unit, November 2003

3.4 Potential detrimental effects of air admission

In parallel with these tests, the risks associated with air admission were considered. It was concluded that:

- The air admitted in the headcover volume must not break the water film in the shaft seal. This is secured by the injection of pressurized clean water between the two seal rings.
- The pressure burst in the headcover due to the incoming air must not cause excessive loading of the thrust bearing or of the headcover structure. This effect is certainly smaller than that of the surge suppressed by the air admission.
- Air injection through ports in the upper distributor ring could be considered as an alternative to the headcover. In this case, the radial forces due to possible instabilities of the annular flow in the upper labyrinth seal must be checked.

The air injection to the turbine must ensure a fast response and a frost-free operation.

The air injection system must be very reliable and must operate during any event that could result in dangerously low pressures in the draft tube.

3.5 Load rejection tests of June 2004, two units with air admission

The air piping was extended to a second unit on the same waterway. The air injection points were modified for air admission between the distributor upper ring and the runner inlet. A simultaneous load rejection of the two units at 75 % load was tested in June 2004. The air discharge was 2.5 Nm³/s on average over the first 10 s of air injection.

Figure 6 shows the draft tube pressure in one of the two units for this 2 x 75% power load rejection test compared with the 100% power load rejection of one unit. The pressure levels are offset to fit the initial steady-state operation to the same pressure although the initial pressure should be about 0.5 mWC greater with 2 x 75% power due to the rise in tailwater level.

Air admission started before unit trip. This explains the small pressure rise before $t = 0$. The draft tube pressure drop is greater than with 1 x 100% because of the greater kinetic energy in the tailrace tunnel. A pressure surge

follows the pressure recovery. This surge shows up in the draft tube, headcover and penstock pressure. It has approximately the same magnitude as in the load rejection of one unit at 75% without air injection, but it is less sharp, less likely to cause mechanical damage.

The maximum speed rise was 140%, about 3% more than with the load rejection of one unit at 75% without air injection. Part of this increase is due to air admission and part is due to the simultaneous tripping of two units.

Before proceeding with the full-power load rejection of two units on the same waterways:

- The distributor closing law must be adapted to limit the speed rise upon load rejection.
- The quantity of injected air must be increased to further attenuate the draft tube pressure drop and to eliminate the surge at 2 x 75% load rejection.

The load rejection of two units at 75% power must be re-tested to ensure that these two improvements are achieved before going on to the next step.

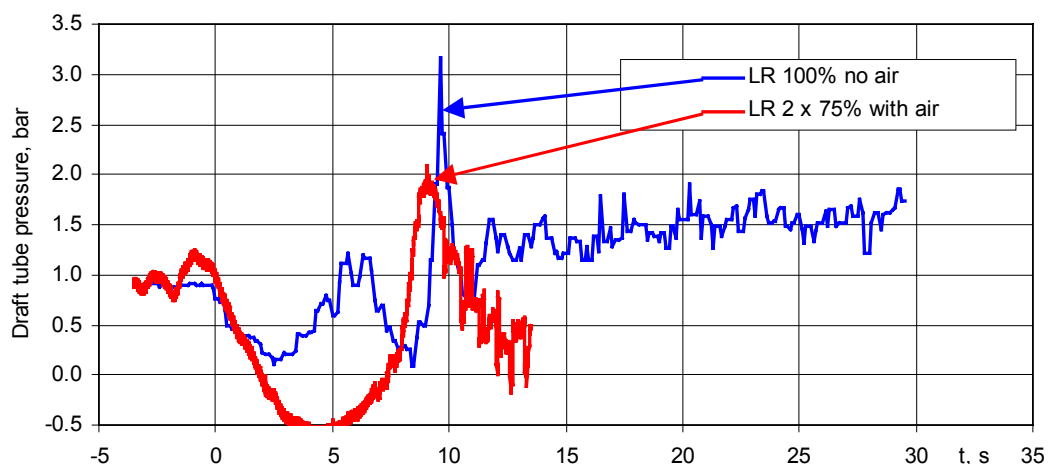


Fig. 6. 75 % power load rejection with air admission, two units, June 2004

3.6 Completion of tests with two units

The final tests of 100% load rejection of two units on the same waterway are planned for September 2004. Operation is restricted until the safety of full power operation is properly assessed. If the results are positive, a permanent protection system based on air admission will be implemented on all units of MES phase 1.

4. Definition of a permanent protection system

4.1 Other options

Options other than a permanent air admission system that were considered were:

- Surge tanks, as initially planned, to absorb the kinetic energy of the water column in the tailrace tunnel with a small pressure drop on a large volume of water rather than with a large pressure drop on the water in the draft tube. Considering the geological conditions on site, this would be very costly and there would be a structural risk on the surge tanks. For the units of MES phase 1, the construction of surge tanks would shut the station down for more than a year. The loss of 700 MW of generation would cause major problems with the national power supply, which is struggling to meet a relatively high load growth.
- Bypass (relief) valves, automatically triggered by rapid distributor closure, to divert the flow from the turbines and limit the maximum speed rise to acceptable values while ensuring a slow stopping of the water column in the tailrace tunnel. For the units of MES phase 1, the installation of bypass valves would involve complicated and costly changes in the powerhouse structure and the units would be out of service for a long time.

IWPC is presently considering a number of options for building downstream surge tanks for the extension. One solution would be to convert the construction adits into surge chambers.

4.2 Design criteria for permanent protection system

The system must deliver a certain quantity of air to each turbine during a certain time after initiation. Initiation must be triggered by any event that could give rise to rapid closing of the guide vanes while the turbine is operating at 50% output or higher.

As it is not safe to operate a pair of units at more than 50% of full load without the air system ready to operate, the system should have sufficient capacity to allow two units to be restarted and brought back to full load after the system has been triggered. This means that the system must be designed to deliver enough air for two consecutive air admission events.

The air supply system must reliably detect any situation where air admission is needed and trigger the opening of the valves. From this it follows that, at the very least, the system must be duplicated so that the failure of a single component will not result in a failure of air admission to a turbine.

The proposed system for delivering air is illustrated in figure 7. The options considered and discarded included an independent system for each turbine, a system with one pressure vessel and one set of control valves for each pair of turbines, and a system with two pressure vessels to supply air to all four turbines via eight control valves.

The main features of the recommended system [2] are as follows:

- Each turbine has two control valves supplied from different air vessels and triggered and operated by independent control systems. As far as possible, the design eliminates the possibility of both control valves failing to operate due to a single cause.
- Each pressure vessel is sized to provide all the air required by both turbines for a single event.

When the system is operating normally, all four valves will operate when a triggering event occurs. The orifice downstream of the valves will control the air supply to the turbine so, even though both valves have operated, the air supply to the turbine will be only slightly greater than if a single valve operated. At the end of an air release, the pressure vessels will therefore still contain enough air for a second operation. This means that it will be safe to restart two machines on the same waterway and operate them at a full power immediately after the air system has been triggered. It also ensures that enough air will be injected if one of the systems fails to operate.

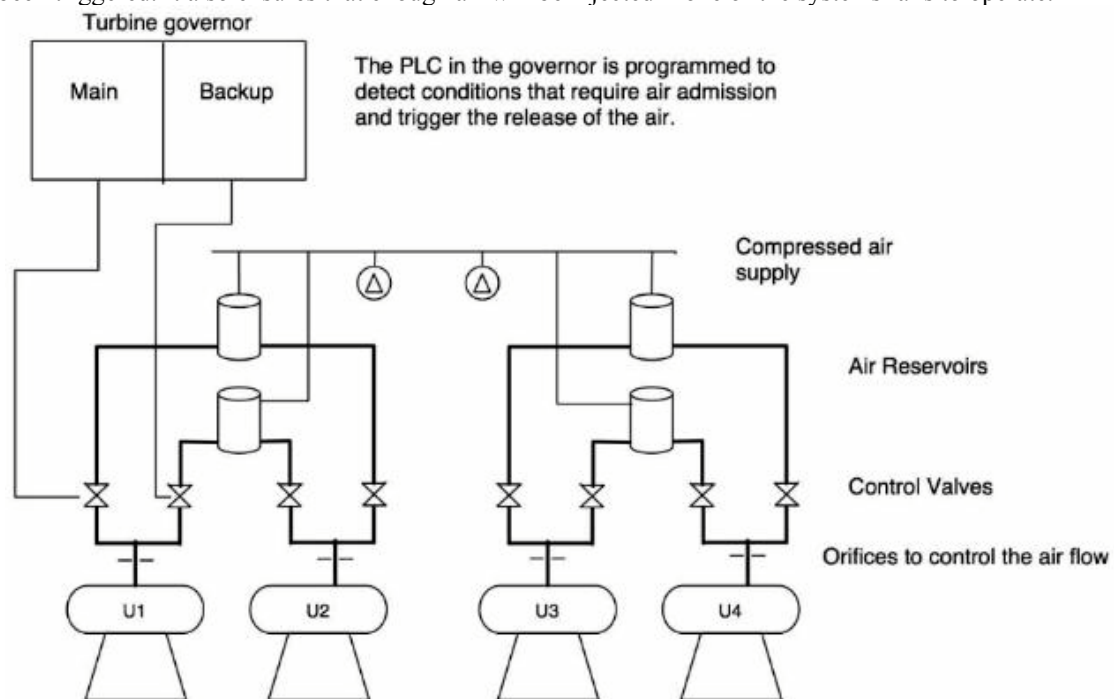


Fig. 7. Proposed air admission system – conceptual sketch

5. Conclusions

The basic problem is that of mass oscillation of 47'000 tons of water moving at over 3.5 m/s in the tailrace tunnel. This represents a large momentum that cannot be absorbed in a satisfactory way with acceptable draft tube pressure drop and rise of rotational speed.

To solve this problem, the panel recommended the injection of air into the turbine. Air injection through the headcover proved to be satisfactory. The final design of the air injection system will be done after a load rejection test with two units at 100% confirming the necessary quantity and duration of air injection.

This use of air admission is innovative. The authors could not find any documented example of a similar problem and solution.

The proposed solution is an active safety concept, depending on a controller action to protect the system from a major failure. An engineer normally feels more comfortable with a passive safety concept. The panel was unable to identify any practical way of modifying the phase 1 units to give passive safety. Even for the extension units, implementing a passive safety system (surge tanks or bypass valves) would be very costly.

When there is any doubt as to the ability of a hydropower plant to handle load rejection or when passive safety devices cannot be built, the designer must consider that state of the art water hammer calculations have a limited accuracy in terms of speed rise prediction, and do not model 3-dimensional two-phase flows that may cause unallowable pressure surges. Large safety margins must be allowed.

The experience gained at Masjed-e Soleyman shows that the injection of compressed air can reduce the risk of transient problems during load rejection for turbines that discharge into long tailrace tunnels. The technique could be useful in underground power plants where the potential for power increase is limited by the risk of excessive negative surges in the draft tube.

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References

1. **Asfia A., Danisovic I., Nonaka T., Subanovic V., Zorc V.**, "MeS HEPP – Hydromechanical & electrical equipment – History of load rejection tests with various closing laws", Moshanir – Lahmeyer International – Nippon Koei note, 2003.
2. **Brekke, H., Jacob, Th., Leyland, B., Pejovic, S.**, "Masjed-e Soleyman – Transient problems upon load rejection", Panel of experts report, IWPC, 2003.
3. **Jacob, Th., Prénat, J.-E.**, "Francis turbine surge : discussion and data base", 18th IAHR Symposium, Valencia, 1996.
4. **Jacob, Th., Regamey, J.-M.**, "Masjed-e Soleyman – Hydraulic surge during load rejection", Stucky notes 4563/2001, 4563/2101, and 4563/2104, 2003 - 2004.

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