FROM ENERGY DISSIPATION TO ENERGY PRODUCTION IN AQUEDUCTS
TAILORED SOLUTIONS FOR COMPLEX PROBLEMS
THE CASE OF MONTE CASALE PLANT

SUMMARY

This report describes the planning work to find solutions to a variety of problems experienced in operating an important aqueduct system in Northern Italy, by converting water flow into energy production.

Detailed information is provided regarding technical problems faced, possible alternatives, and final solutions. The result is a hydropower plant showing several peculiarities, which could be helpful at similar situations elsewhere in the world.

GENERAL INFORMATION

The Acquedotto della Romagna is a broad aqueduct system, designed to catch, collect, store and distribute water for drinking and other purposes in more than 40 municipalities located in the Riviera Romagnola (Italy) and the Republic of San Marino (Figures 1 - 2).

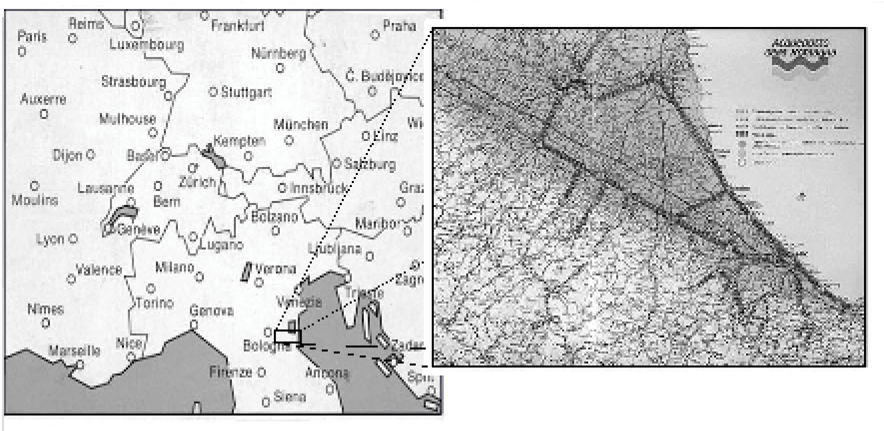

Figure 1 – Area Location

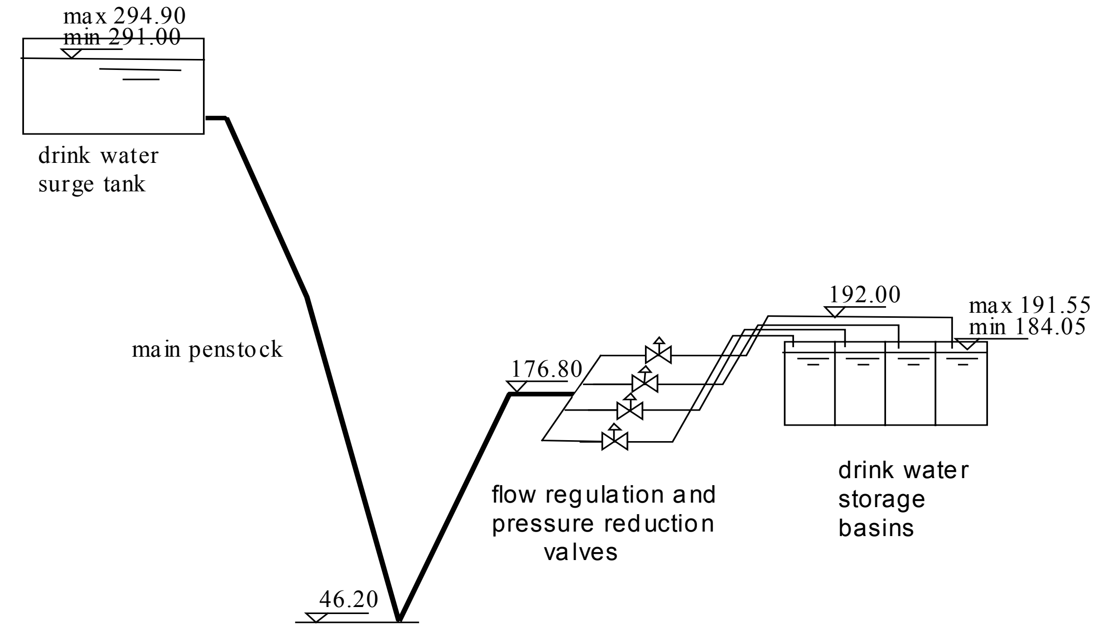

Figure 2 – Hydraulic sketch of existing works

Since the beginning, the conceptual philosophy of the system was to take advantage of the favourable topography and let the water flow only by gravity from the catchment basin all the way to the end user to supply 900.000 residents (and several millions of tourists during the summer) with quality drinking water. The system is owned and operated by Romagna Acque S.p.A., a consortium of local municipalities.

Water is collected from several creeks in the mountainous area between Ravenna and Florence, and stored in the Ridracoli basin (capacity 30 Mm^3) created by an concrete arc-gravity dam, 430 m wide and over 100 m high. Since the beginning this dam was built as a multiple-purpose structure, to store water both for aqueduct use and for energy production, as well as cutting peak flows during overflow periods.

The first stage making use of the water storage is a hydropower station of 8MW capacity, which is fed through a pressure tunnel system with a steel penstock almost 7 km long. Downstream of the power station is a water filtration plant, rated for a maximum production of 3 m^3/s of drinking water, followed by a first underground storage basin, made in concrete, with a capacity of 10.000 m^3. This is the point where the plant modification begins (Figure 3).

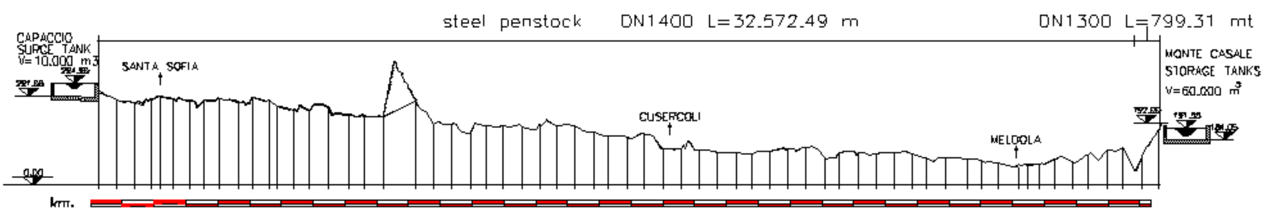

Figure 3 – The main penstock

The water level in the storage tank can fluctuate up to 3,9 m, depending on the operating conditions of the filtration plant and acts at the same time as a surge tank for the main penstock, which is made of welded steel pipes, at a length of 33 km, using DN 1400 mm (Figure 4).

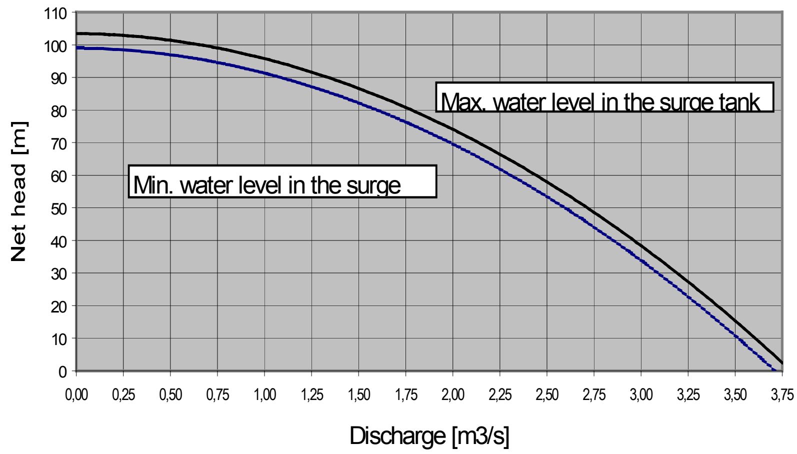

Figure 4 – Flow-head curve

Minimal flows are diverted along the main penstock to feed three villages on the way downstream, but they are playing a marginal role in the general economy of the plant.

Almost all of the flow is directed towards the Monte Casale site, which is located in the centre of the service area. Four underground concrete tanks, each one having a volume of 15.000 m^3, were built here, to play a major role for the whole aqueduct system, to cope with daily fluctuations of water needs with a total capacity of 60.000 m^3. The residual pressure downstream of the penstock mainly depends on the flow rate, due to the prevalent influence of friction losses inside the pipe. The water level fluctuations in the upstream tank have a small influence only as shown in the head loss curve (Figure 5).

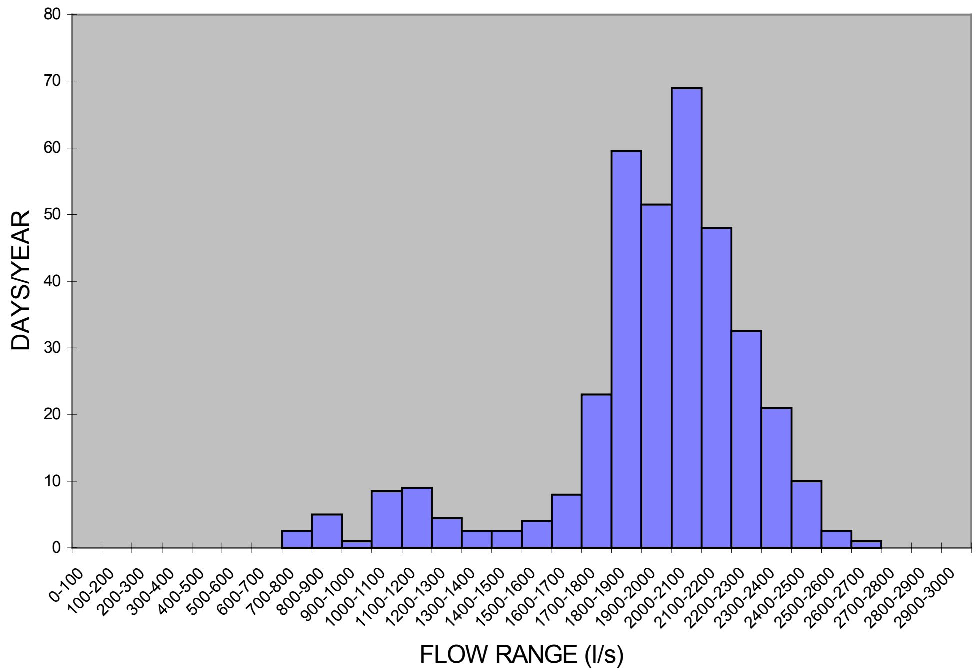

Figure 5 – Available discharge

Just upstream of these basins the main penstock branches out into four pipes of DN 600 mm, each feeding a separate basin. Each pipe is equipped with a DN 600 mm multi-jet valve to regulate the discharge and to dissipate the residual pressure. The multi-jet valve is comprised of two flat disks, one fixed to the valve body, the other one sliding in front of it, driven by an electric servomotor. Both disks are drilled with the same hole pattern. Discharge is maximal and head dissipation minimal when the holes of both disks are exactly in line; the more the sliding disk is displaced, the smaller the openings become, which reduces the discharge.

If necessary, the Aqueduct Manager decides on the set point value of the total discharge in terms of litres per second. Valve regulation to meet the set point value is driven by logic automation with PLC and is monitored via a remote control system.

To complete the plant set up, two pressure release valves are installed upstream of each regulation valve, with calibrated springs set to open when the water pressure exceeds the static pressure by exactly 1,69 bar. To avoid any unnecessary risk, opening and closing of these valves is fully automatic, strictly controlled by the action of the calibrated springs to prevent stresses and a possible rapture of the main penstock, since any failure could result in a water shortage which could have dramatic effects for the local economy.

PROBLEMS ENCOUNTERED

Since early test runs, the main penstock has shown to be very sensitive to flow changes, due to intrinsic problems, such as its extreme length and small diameter, minimal wall thickness of the steel pipe and potential sources of deflected pressure waves along the penstock.

During flow regulation tests, the main penstock showed excessive vibrations, probably originating from resonance effects between pressure release valves placed on the same line, or on different lines. Despite several modifications and corrective measures it was impossible to overcome this problem until now.

The relevance of vibrations was so severe that it had to be decided to operate the plant at flow changes slow enough to maintain a pressure rise below 1,69 bar of the set point of the pressure relief valves, but still leave them in place and functional as a last safety measure.

Practically any flow change had to be executed in small steps of 0,2 m^3/s at intervals of not less than 75 seconds. Thirteen years of experience have shown that any regulating action of less than 0,2 m^3 in 75 second intervals, irrespective of the closing mode (continuous or stepped), would keep the penstock pressure fluctuations within the range of the relief valve setting.

By following this strictly empirical procedure, any resonance and vibration problem along the penstock could be avoided, but this method was not fool proof, since any problem with the PLC could drastically reduce the required time interval between regulation steps.

Another problem found no chance of resolution until now: The wear factor of the regulation valves. Due to the constant flow/energy dissipation, these valves were subjected to continuous wear, mainly the flow regulating disks and servomotors. Much maintenance was necessary to keep wear within tolerable limits, with subsequent costs in terms of workforce and spare parts required.

REQUIRED SPECIFICATIONS FOR THE NEW PLANT

The new hydropower station in Monte Casale was conceived to provide an intrinsically safe, non-dissipative device for flow regulation, to find a reliable and definitive solution to the above mentioned problems.

Several alternatives were studied but, to be sure, an international tender was issued, where nearly all reputable turbine manufacturers were invited, to provide acceptable solutions.

Specifications stipulated for the new plant, in order of relevance:

1) Regulation system of the hydropower plant to be fully adaptable to the requirements of the aqueduct, its main function being limited to opening/closing of the turbine guide vanes until the discharge set point was reached. In case of a fault on the electrical mains it should stop the turbine at acceptable closing times and re-start it as soon as normal conditions were re-established on the grid.

2) No reduction in water quality when flow passes the regulation devices and turbine runner(s).

3) Turbine(s) causing no flow gradient during transient conditions in case of a generator trip, due to overspeed condition.

4) Regulation system being able to perform extreme slow opening / closing sessions in an intrinsically safe way, due to remote or local control commands, or in case of a grid failure. Under no circumstances should the flow gradient be allowed to exceed the limit of 0,2 m3/ 75 seconds, meaning it will take 1125 seconds (equals approx. 19 minutes) for a complete closing cycle at a flow of 3 m3/s.

5) Turbine(s) being able to operate at flows between 0,7 and 2,7 m3/s, at variable net head conditions ranging between 97,12 and 48,10 metres of static head (Figures 5, 7, 8, 9).

6) Turbine(s) and regulation system being able to operate also in a range where the ratio power vs. discharge is reversed when compared with normal hydropower stations (flow ranges exceeding 2,2 m3/s in figure 8).

7) Generating set for grid parallel operation only.

8) Simple design of the power train, with special attention to simplicity and ease in operation.

9) In case of revision purposes or due to a malfunction that could lock the turbine guide vane in a closed position, a by-pass line with a by-pass valve was needed, that performed the very same functions as the turbine in regards to flow control and timing.

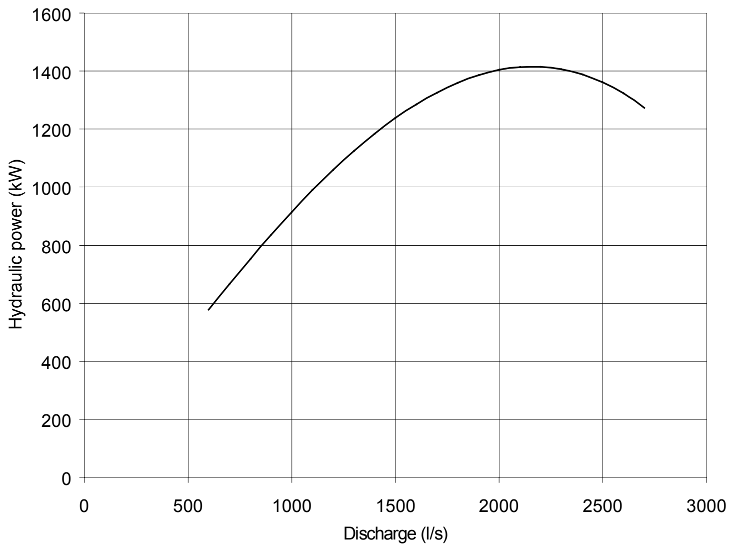

Figure 7 – Power-discharge curve

POSSIBLE ALTERNATIVES

As for turbines several alternative solutions were perused, since some specification requirements of the new plant were quite unusual for conventional minihydro. Pelton, Francis and Crossflow machines were considered; following is a summary of pro and cons of each turbine type:

Pelton Wheels

Advantages	Disadvantages
• Reliable solution - thanks to jet diverters - to prevent turbine runaway speed and water hammer in the penstock.	• Head/discharge range available at site is far from the typical application range for this type of turbine. It would be necessary to install several multi-jet turbines to cope with existing conditions.

• The turbine being an impulse type machine, upstream and downstream sections of the plant are hydraulically disconnected.	• Need to install turbines at a higher elevation with respect to storage basins, and subsequent additional head losses. • Higher complexity, due to the need of installing several units. • Larger powerhouse and more costly civil works, for the same reason. • Complex and expensive control functions, for the same reason.

Francis Turbines

Advantages	Disadvantages
• Head range available at site well suited for this turbine type. • Opportunity to install turbines with backpressure or at higher elevation with respect to storage basins. • Very good efficiency, in particular when two machines are installed and optimally sized for different head-discharge ranges. • Complex plant, due to the need of installing at least two machines, but simpler than using Pelton wheels. • Medium-sized powerhouse required. • Complex but less expensive operation.	• More or less impossible to carry out an intrinsically safe solution with respect to transient hydraulic conditions. Being a reaction type turbine, flow will be continuous from the surge tank to the storage basins: Under these circumstances, any perturbation or flow disturbance could be transferred upstream to the main penstock. • Depending on the designated specific speed, the runner could induce discharge gradients in transient conditions between rated speed and overspeed. Even at best scenario it would be necessary to install a by-pass system for each turbine to reduce overspeed time. • For the necessity of flow variation several units would be required.

Cross-Flow Turbines

Advantages	Disadvantages
• Head/discharge range existing at site well suited for this turbine type. • Opportunity to exploit the whole discharge range from 0 up to 2,5 m^3/s with one single turbine. • Complete hydraulic disconnection between upstream and downstream sections of the plant - the turbine type being an impulse machine. • Possibility to offer an intrinsically safe solution with respect to transient hydraulic conditions by reducing the closing/opening speed as much as necessary and by dimensioning the power train to withstand run-away speeds for a long time. No need of by-pass system for the turbine.	• Need to install the turbine at higher elevation with respect to storage basins, with some losses in head. • Total efficiency somewhat lower than with other solutions using several turbines. Anyway, cost-benefit calculations showed that no realistic pay-back period could be granted for additional investments that would be necessary to improve the whole energy potential.

• Possibility to avoid discharge gradients in transient conditions between rated speed and overspeed by customising the turbine. • Good average efficiency throughout the whole head/discharge range. • Simple plant design thanks to one single unit. • Small powerhouse layout. • Easy and inexpensive operation. • Therefore, in spite of lesser efficiency, the lowest specific costs per kWh.	

SELECTION

A crossflow type turbine was selected, and the contract was awarded to Ossberger GmbH + Co (Germany) on a turnkey basis for the supply of power train and regulation system. Civil and hydraulic works, electrical switchboards and electrical connections were awarded to Mattioli Costruzioni S.p.A. (Italy).

The turbine is fed by a new by-pass penstock, connected to the main penstock upstream the energy dissipation system. Taking advantage of the local topography, it was possible to place the new powerhouse at a higher level in relation to the storage basins (figure 8).

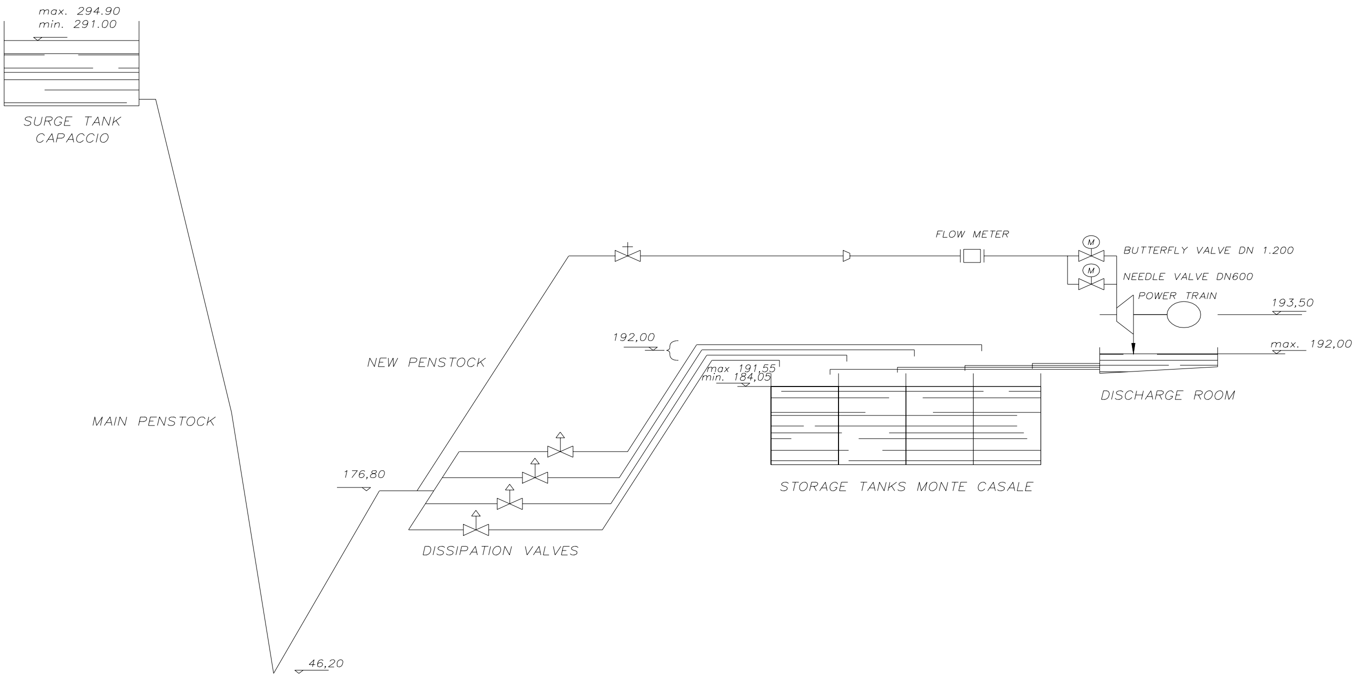

Figure 8 – New hydraulic sketch

Downstream of the turbine, water discharges into a new discharge chamber, where it is calmed and directed towards the storage basins via four new pipelines. Civil structure and hydraulic works were not without complications, since a lot of complex operations had to be performed without affecting the aqueduct service. Water distribution to the consumers was never stopped.

The plant meets the specifications as follows:

1) **Regulation system:** The hydropower plant is equipped with a PLC logic that monitors the proper operation of each component. Technicians working in the aqueduct control room specify the amount of the flow discharge in demand, sending it to the regulator via optic-fibre remote control system. The PLC uses this signal as the set point and opens/closes the guide vanes until the actual flow rate equals the set point. In case of a grid failure the plant is disconnected and the flow rate decreased to zero at closing speeds detailed hereafter; as soon as normal conditions are re-established on the mains, the regulation system re-starts the plant and brings it up to the set point value again.

   Planning and manufacture of the generator protection were subcontracted to VA Tech Elin EBG GmbH of Innsbruck/Austria. Here it was essential to automate the turbine control system to the latest technical standards. The control system optimises and regulates the turbine according to the flow value desired. The process connection to the guide techniques was realised through TCP/IP. All process sequences were visualised in the switchboard.

Figure 9 - Visualisation

2) **Water quality not affected:** All parts of the turbine in contact with water are made of stainless steel; all other metal components (tubes, valves etc.) are made of materials certified to comply with potable water regulations and protected by surface coatings with materials of the same certification. Turbine shaft bearings are mounted outside the turbine casing, to far away to come in contact with water. Guide vane bearings are made of maintenance-free self-lubricated materials (see figure 10).

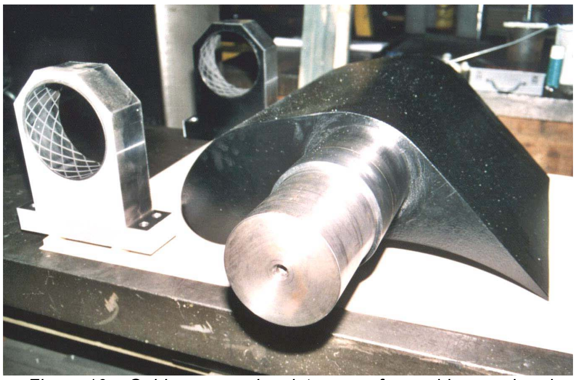

Figure 10 – Guide vane and maintenance-free guide vane bearings

   No oil was used in the regulation system to operate the guide vanes, to avoid any risk of contamination in case of a break in the hydraulic circuit. The only alteration to water quality induced by the turbine is a positive one: While crossing the runner, the water strikes the runner blades twice and discharges as a water-air mixed spray. The final result is increased oxygenation to the top quality rating of the aqueduct water.

3) **No dangerous flow gradient during transient conditions:** OSSBERGER GmbH + Co provided a special design for the turbine: Model tests performed at their own test facilities confirmed that the selected geometry granted a flow gradient smaller than 0,2 m3/s even in the

worst case scenario - grid disconnection at maximum output. Figure 11 shows the authors during acceptance of the turbine runner at the manufacturer's work shop.

Figure 11 – Acceptance test at work shop

4) Slow opening / closing actions accomplished intrinsically safe: This specification was exactly complied with, and several measures were necessary to be fulfilled:

4.1) No hydraulic servomotor was used: Apart from a potential contamination in case of a break of the hydraulic circuits no hydraulic cylinder manufacturer would grant a constant speed over a number of years. A minimal leakage in the servo-valves or gaskets could seriously affect the closing speed of guide vanes and butterfly valves, exceeding overpressure limitations. All flow regulation devices were equipped with DC servomotors continuously powered by a DC system with buffer battery.

4.2) DC servomotors are dimensioned to operate flow regulation devices by step-down gears to reduce the speed. When the regulation system provides an opening or closing signal, the servomotor will run continuously until the desired position is reached. As a consequence, the only way to increase the speed action would be to replace the gear ratio, a fact that cannot be done unintentionally: This is an important improvement when compared with time-delayed impulse devices now acting on dissipation valves. The mechanical transmission is irreversible, so, in case of a fault on the servomotor, the flow regulation device is kept in position and cannot perform undesired movements.

4.3) As an additional safety criterion it was decided to extend the time interval for the flow regulation. Limits set by the bid specifications stated a closing time not less than 1125 seconds for a complete shut-down or start-up cycle at a flow of 3 m3/s. As a matter of fact, the timing was extended to 2140 seconds for the guide vane servomotors, and even more for the valves, to complete a 2,5 m3/s flow reduction cycle.

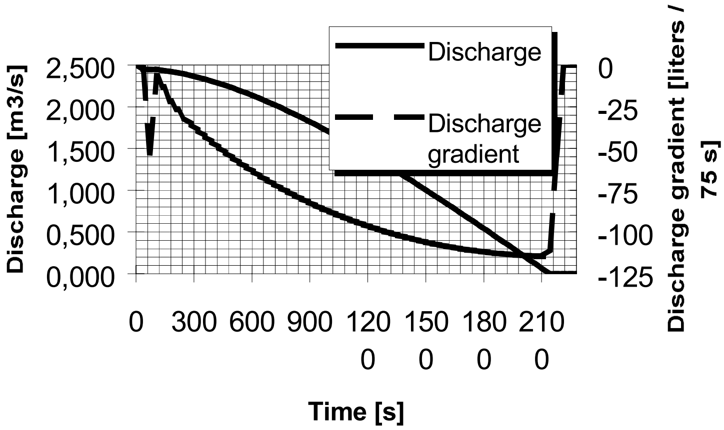

Figure 12 – Discharge vs. turbine guide vane opening

4.4) The turbine was subdivided into two cells of equal size, instead of the usual ratio of 1/3 to 2/3 which permitted design of guide vanes, servomotors and flow regulation system being identical for both cells.Tests of the Ossberger crossflow turbine showed, that the discharge is a linear function of the guide vane position. This function offers a reliable basis to start a simple control logic (figure 12).

4.5) Automatic valves installed upstream of the turbine are driven by electric servomotors, for the same reasons as mentioned under para. 4.1) and 4.2). The task of these valves is to effect the shut down procedure of the power train in case of a fault in the servomotor control circuit which operates the guide vanes of the turbine.

The original plan was installation of a DN 1300 mm butterfly valve in front of the turbine, but later studies showed that the flow gradient limits would require a closing time of nine hours or more to stay within limits. It is a well known fact, that the closing timing of a butterfly valve is not linear to the flow discharge; it was even more surprising to learn, that a disk closure of 80% reduced the discharge only by 6%, while a 90% flow reduction occurs throughout the final 5% of the closing turn. Under these conditions a butterfly valve alone would be insufficient for the intended purpose. Gate valves and ball valves showed better behaviours, but were still unsuitable for the intended application. The final solution was the use of two valves: A butterfly valve DN 1200 mm and a needle valve DN 600 mm placed in parallel. When needed, the butterfly valve would start the closing action immediately, which would be completed in 1250 seconds, while the needle valve was kept open by means of a mechanical interlock to prevent any action of the needle valve until the butterfly was fully closed. At this stage, discharge is reduced from 2,5 to 2,17 m^3/s and after an additional delay of 250 seconds the needle valve commences its closing cycle, which lasts 1680 sec, for a total of 3180 sec. Despite the action time being much longer than specified in the tender, the required modification just complied with the tender regarding the flow gradient, as shown in figure 13.

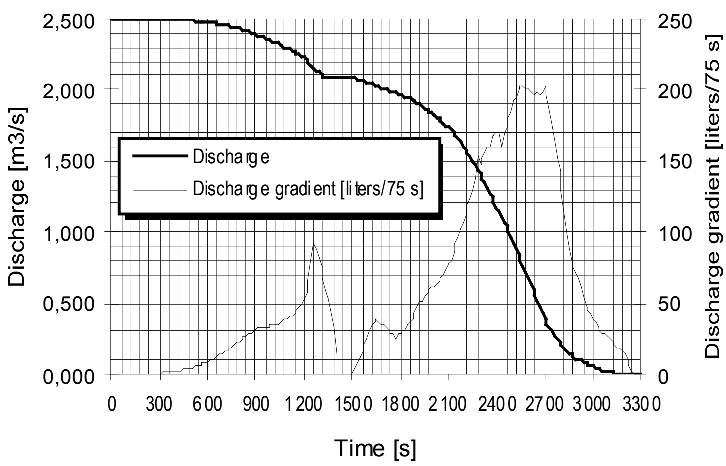

Figure 13 – Discharge vs. valve opening

A further study was necessary to calculate the behaviour of the two valves operating in parallel, considering the influence of pressure waves emitted by the main penstock. The design of the valve was conducted by ERHARD Armaturen (Germany).

4.6. One event not covered by the above mentioned precautions is the contemporary failure of both servomotors operating the turbine guide vanes as well as both servomotors operating butterfly and needle valve when an emergency shut-down occurs: Under these circumstances the power train would speed up to a runaway speed which, in the worst case (full output), would reach 2,7 times the rated speed. To cover such an event, the whole power train had to be designed and tested to withstand stresses associated with such runaway speed for a prolonged time limit.

Head/flow range: The turbine can exploit the whole range of flows from 0 and 2,5 m^3/s. When the aqueduct scenario requires a discharge exceeding 2,5 m^3/s the turbine is shutdown and the aqueduct is controlled by the energy dissipation valves. Based on hourly flow data obtained over the past ten years by Romagna Acque, the hydropower station should be operating for 8674 hours annually, i.e. 99% of the time, while the emergency conditions passing the flow through the energy dissipating valves will be limited to only 3,6 days per year.

To limit the maximum exploitable discharge to 2,5 m^3/s means only a 1,27% loss in terms of available flow and only a 0,85% loss in terms of energy production, due to the fact that residual heads are very low at high flow rates.

6) **Operation on the unstable side of the power / discharge curve:** The regulation system maintains the flow rate requested by the aqueduct controller at set point. Because power generation is only in parallel with the mains, there is no problem of working in a range where an increased power output results from a flow reduction.

7) **Generation - grid parallel only:** The asynchronous generator, made by Loher AG (Germany) can only generate when grid connected. No self-excitation is possible, since the capacitors used to improve the power factor are disconnected from the generator at the same time the main breaker is opened by any tripping device. The 14-pole asynchronous generator IEC construction size BG 710 is rated at 1045 kW at a nominal speed of 432 r.p.m. and rated voltage of 6000 V. The coil winding insulation is moisture proof and rated for thermal class F – operating at thermal class B. High emphasis was based on the electric design regarding the efficiency, using optimal noise reduction measures and tubular cooling coils. Figure 14 shows the generator's noise emission in the field. At full load the generator obtains an efficiency of 96 %, at quarter load an efficiency of almost 92 %, which is quite remarkable.

Figure 14 – Generator during test

The particular mechanical demand placed on the generator design is the run-away speed of almost 3 times nominal speed (1100 r.p.m.) for up to 2 hours, which was solved by Loher using a special runner design in combination with special bearings. The generator weighing 13,5 tons was also equipped with anti-condensation space heating elements and bearing temperature, stator winding temperature and vibration monitoring devices.

8) **Simple construction - easy and inexpensive operation**.

The specification was met by providing the following:

- A single power train, directly coupled,
- An asynchronous generator,
- Grease-lubricated roller bearings for turbine and generator shafts,
- Self-lubricated bearings for turbine guide vanes.

The only maintenance work necessary is:

- Greasing of turbine shaft bearings (once per month - no shut-down required).
- Grease replacement of turbine shaft bearings (once per year – requires less than two-hour shutdown).
- Grease replacement and used grease removal at generator shaft bearings (once per year – no shut-down required).

CONCLUSION

The experience in planning the Monte Casale plant showed that a close co-operation between the utility management owning the aqueduct system, and experienced planners for civil works, equipment manufacturers and consultants, even in context of an international project, proper answers to technical problems can be obtained, which appeared to be impossible at first glance.

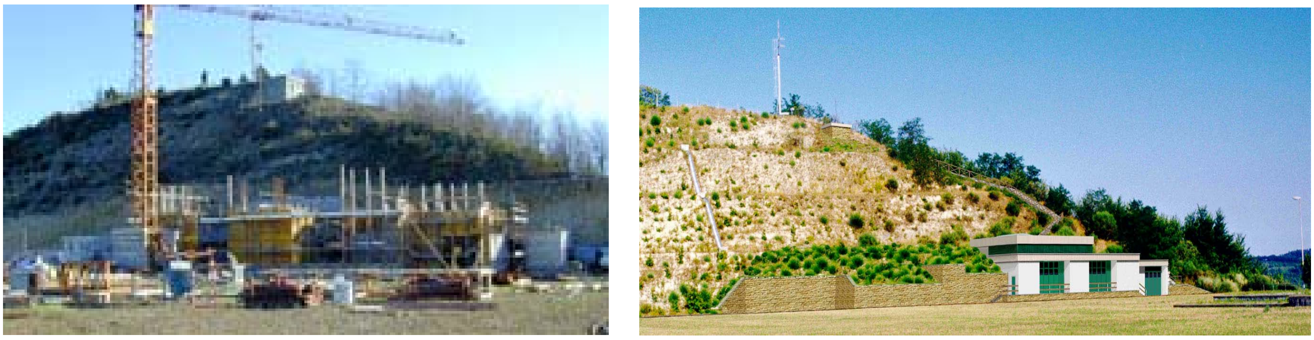

Figure 15 – Work in progress and future result

Authors: Ing. Michelangelo AMATO, ITALPERFO S.r.l, technical consultant for minihydro
Ing. Piero FLAMIGNI, COGEST S.r.l, planner for civil and aqueduct works and director of works.
Ing. Guido GOVI, ROMAGNA ACQUE S.p.A. project manager for the utility owning the plant.
Helmut Erdmannsdoerfer, MBA, Department Manager OSSBERGER GmbH + Co

OSSBERGER
OSSBERGER GmbH + Co
P. O. Box 425
91773 Weissenburg / Germany
Tel: 00 49 (0) 91 41 / 9 77 -0
Fax: 00 49 (0) 91 41 / 9 77 20
Web: www.ossberger.de
E-Mail: ossberger@ossberger.de