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A MULTI-PATH ACOUSTIC FLOW METER TESTED IN PENSTOCKS WITH VELOCITY DISTRIBUTION DISTURBANCES

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Abstract

Using ACCUSONIC 7510 P penstock protection system in two ENEL S.p.A power plants the acoustic flowmeter behaviour was tested in presence of velocity distribution disturbances.

IEC 91 standard, asking for a straight length of upstream conduit before the measuring section, are not always observed in protection system because the sections are in positions not designed for this installation, due to the whole penstock protection.

In the installations presented in this paper the measuring sections are positioned in a correct mode in only one of the two measuring sections while the second one is positioned near disturbances as valves or bends.

In the first of the two power plant tested the upstream measuring section is positioned according to IEC standard and downstream section is positioned after a 45° bend.

In the second power plant there are three penstocks that feed in parallel the hydraulic machinery with various kind disturbances as butterfly valves or connections between the penstocks.

The installed acoustic flow meters are 4 or 2 paths type.

In the paper the differences between upstream and downstream flows with all the paths well running are analysed and the performances of the flowmeter are tested against anomalies presented in one or more acoustic paths with guaranteed constant discharge.

Using the recorded data with various flows a new weight for each acoustic flow was calculated with a reduction of the difference between flows at the beginning and the end of the penstock.

1. Introduction

For a few years multipath acoustic flowmeters have been installed at the beginning and end of penstocks in order to protect the latter. If the penstock is in good working order and if there are no water outlet or inlets along the section between the two flowmeters, the difference in discharge is null, whereas when there is a sudden water loss due to breakage, the flowmeters indicate the anomaly and activate a protection system which envisages the closure of the on-off valves at the beginning of the penstock.
In order to protect the entire penstock the plant operators have to choose sections for the installation of the ultrasonic discharge measuring devices which are as close to the beginning and end of the penstock as possible. In such conditions, the disturbing elements situated upstream or downstream of the measuring sections create distortions in the flow field and this makes it more difficult to calculate the discharge accurately. Non observance with the straight length upstream and downstream of the measurement sections as envisaged by (IEC 41-1991) may occur on only one of the two sections or on both. In these conditions it is necessary to guarantee that in the entire discharge variation range, the differential discharge is null when there are not leaks.

2. Main errors of the acoustic flowmeter

The principle of the acoustic method has been extensively described in the literature and in appendix J of the above-mentioned IEC standards.
The errors to be considered are of three types:
- a) errors in velocity measurements in the individual acoustic paths
- b) velocity integration errors over the entire section
- c) other errors attributable to other causes

Errors of the a)-type are due to installation errors (geometric errors which include the length of the acoustic paths, the angle of the paths in relation to the axis, the distance of the paths in relation to the axis of the penstock). Altogether they can reach a value of 0.2÷0.3 %.
Errors of the b)-type derive from the ovality of the penstock and from uncertainties in the definition of the velocity profile, which is particularly high when the flow is not fully developed; they particularly depend on the number of acoustic paths and are in the order of 0.1÷0.2 % for a 4-path flowmeter and increase to a few percent for single-path flowmeters. An optimized integration method, known as OWICS (Optimal Weighted Integration for Circular Sections) developed by (Staubli et Alii 1996) makes it possible to reduce the integration error to below 0.1 % for velocity distributions in smooth and rough penstocks that comply with logarithmic laws.
Errors of the c)-type are the most difficult to calculate since they are triggered by the hydraulic conditions upstream and downstream of the section, i.e. to the type and the distance of the disturbing elements and their effect is greatest when single-path flowmeters are used.
On this subject, particular mention should be made of the important research conducted at the Turbomachinery Laboratory of the Institute of Technology in Lausanne through which they were able to calculate the error of an eight-path acoustic flowmeter

(arranged on two crossed planes in groups of 4 for each plane as recommended in the above-mentioned IEC 41/91 standard) in the presence of disturbed conditions in the flow field (Bruttin 1996).

We should also mention the uncertainty linked to the protrusion of the acoustic transducers within the penstock; the protrusion value, in fact, is still under investigation and has yet to be defined in the IEC Standards, having only been defined in the Japanese Standards (JEC- 4002), and it gains in importance in the case of small diameters (below 2 m). A more complete description of all these errors can be found in the literature (Lowell 1979, Grego 1987, 1996, Sugishita 1996, Nakamura 1996).

3. Application of acoustic flowmeters for the differential protection of the penstock

3.1 Plant A

The plant to be protected consists of a penstock which was built in the 1940s and extends for a length of 726 m with a geodetic height of 377m. It feeds three horizontal-axis Pelton turbine groups, each of which has a generating capacity of 19.7 MW, with a discharge rate of 5 m^3/s.

We chose to locate the outermost discharge measurement sections in the valve hall (upstream section) and immediately upstream of the production groups for the downstream section, respectively. Fig. 1 shows the upstream installation position with a straight lenght of about 27 m, which is equal to 15 diameters; this position is optimal since it amply meets the IEC requirements to guarantee a correct velocity distribution; on the other hand, in the downstream installation it was necessary to locate the measurement section immediately downstream of a 45° bend (Fig.2), with only 2 diameters of straight lenght i.e insufficient for guarantee a fully developed flow.

This problem was partially overcome by choosing a 45° configuration with 4 acoustic paths positioned symmetrically in relation to the bend plane at distances of ±0.30902 R and ±0.80902R.

In order to trace the positions of the intrusive type acoustic transducers and to drill holes in the penstock we worked from outside on both sections using a procedure which the company that supplied the equipment recommended to us and which we then perfected, whereas for the installation of the transducer mounts access could be gained from the inside and this made it possible to align the transducers of each acoustic path properly and to get accurate measurements of both the diameter of the penstock and the lengths of the acoustic paths.

The geometric parameters of the installation are shown in Fig.3 for both the upstream and downstream sections. We should point out that in the case of the downstream section, the difference of about 2° in the angle of inclination of the acoustic paths from the theoric value of 45° is due to the presence of the armour plating of the penstock which meants that the transducer mounts had to be housed in the slot as shown in Fig.2. Despite this difference, however, the acoustic signal is transmitted and received properly as guaranteed by the supplier of the equipment and this was verified when the system was activated.

3.2 Plant B

The plant to be protected is equipped with three penstocks which were built at the beginning of the twentieth century and extend for a length of about 1066 m, with a geodetic head of 467 m; they feed a group of horizontal-axis Pelton turbines with a capacity of 14.5 MW and a discharge rate of 3.8 m^3/s.

The data acquisition equipment and the acoustic transducers chosen for measuring the discharge are identical to those used in plant A. The differential protection system consists of two acquisition units (one upstream, the other downstream), each capable of handling 8 acoustic paths that are subdivided to optimize the measurement of the velocity in the three penstocks to be monitored simultaneously Four paths were chosen both upstream and downstream in one penstock (the one with the most disturbed flow field) and two paths for the other two, as shown in Fig.4.

Since the system is only able to handle two discharges per monitoring station (upstream and downstream), we decided to consider the sum of the flowrates of penstocks n. 1 and 2 as the first discharge, and the flowrate in penstock n. 3 as the second discharge.

The position of the discharge measuring sections was conditioned by the geometry of the penstocks, which in the course of their working lives have undergone maintenance work, as well as by whether there is easy access from outside and by the position of the disturbing elements which led to the flowmeters being installed at the beginning of the penstocks upstream of the butterfly valve in the case of penstocks 1 and 3 and downstream in the case of n.2 (see Fig. 5). Four acoustic paths were chosen for the latter penstock since the kinematic conditions are the most disturbed of the three due to the immediately upstream location of the valve.

In the downstream monitoring station, the location of the measuring sections was not only conditioned by the presence of disturbing elements, but above all by whether there is easy external access to the penstocks which is indispensable for the installation of the transducer feedthroughes.

In this case the disturbing elements are present downstream of the measuring sections, as shown in Fig. 6, since all three penstocks have a long straight stretch of over 30 diameters upstream of the acoustic flowmeters. Based on the same considerations that were made for upstream flowmeters, we decided to equip the section with the most disturbed conditions with four acoustic paths i.e. penstock n.1 which is in conditions that are less regular than those in penstock n. 3.

The geometric parameters of the installation of the stations upstream and downstream of plant B are given in Fig. 4. We should point out that the angles of inclination of acoustic paths are around 45° upstream in penstock 2 and downstream in penstock 1, whereas the others revealed values of around 51° upstream and 29° downstream. This is because 32 transducers were supplied for a 45° configuration as we had originally envisaged protecting only two of the three penstocks, and abandoning the third. Therefore the configuration with two acoustic paths positioned at ±30°, as shown in Fig. 4, entails θ angles of the acoustic paths in relation to the 29° axis for the transducers used in a 45° configuration in the external paths (54°) and 51° for the ones used in the internal paths (18°).

The characteristics of the elements disturbing the acoustic flowmeters in plants A and B are summarized in Tab. 1, which reports the number of diameters of a straight penstock upstream and downstream of the section where acoustic flowmeters have been installed, as well as the type of disturbance condition .

4. Characteristics of the measuring equipment

The system adopted for measuring the differential discharge is essentially made up of two acquisition units and of acoustic sensors, four in plant A and 8 in plant B for each discharge measuring station. Both upstream and downstream of the penstock there is an electronic unit (connected to the transducers by cables) which is capable of processing the discharge parameters; in the designed configuration the two units, which are identified as “master” (the one installed downstream) and “slave” (the one installed upstream), are linked by a modem with an optical fibre cable or telephone duplex cable.

Communication between the two units permits the modification of the parameters by either unit, the acquisition of measured data, as well as the ability to control the “slave” unit through the “master” unit.

The discharges, which were determined for the upstream and downstream sections using the Gauss-Jacobi integration technique, which in turn uses Techbycheff polynomials in compliance with IEC Standards, are compared in the master unit which activates a relay alarm system if the thresholds are exceeded; these threshold values are imposed by the user and can be regulated according to the plant characteristics.

The system works with DSP (Digital Signal Process) technology which is used to run the transducers, process the signals and then to determine the discharges.

The system continues to function properly even if one or more of the acoustic paths breaks down. In fact, when the signal from an acoustic path is no longer readable, the last velocity value to be considered correct is used to calculate the discharge until the consecutive number of incorrect measurements exceeds the value of a suitable parameter chosen by the operator.

When this value is exceeded the acoustic path will be defined “out of operation” and as a result its data will be rejected; nevertheless, the system will continue to test the path to monitor the duration of the anomaly in order to be able to use the data again if the acoustic path starts working properly .

If one or more of the acoustic paths start to malfunction, a process comes into effect which calculates the discharge using the velocity data which are considered correct and determines the rejected parameters from a table of “reference components” of the velocities recorded during system testing with over 1000 readings taken at the nominal discharge value of the plant.

Every discharge upstream and downstream of the penstock is measured by each processing unit using the relation:

$$Q= S*A*\sum_{n=1}^{m} *W_n*V_n \qquad (1)$$

where:

S= the value of the “flow scaling” determined by the operator

A= penstock area

m= number of acoustic paths
W_n = weight of path n , 1≤n≤m
V_n= velocity of the acoustic path calculated by the system, 1≤n≤m

Parameter S makes it possible to correct the discharge value in order to compensate for any anomalies in the kinematic field caused by disturbed conditions that are too close to the measuring sections, valid for the plants discussed in this report, thereby cancelling the difference in discharge that was detected between the upstream and downstream flowmeters if there are not leaks.

5. Tests carried out on plant A and results

When the discharge measuring system was activated in the two sections upstream and downstream of the penstock, a difference of 1.2 % was detected between the indications of the two flowmeters at the nominal discharge and therefore the downstream flowmeter measurement was corrected from the upstream flowmeter measurement; the upstream flowmeter was installed (as described in paragraph 3.1) at the end of a 15-diameter straight lenght which complies with IEC Standards 41/91.
In order to test the performance of the flowmeters, three sets of tests were carried out:
in the first set: tests were conducted on the difference between the downstream and upstream discharges with varying discharges ranging between 40 and 100% of the nominal discharge i.e. to check whether the 1.2% correction remained constant during the full operative range,
in the second: operating all the acoustic paths in the upstream sections, we monitored the difference in discharge between the two sections, disactivating any one or two of the four acoustic paths to simulate a possible breakdown of the transducers;
in the third: velocity discharge measurements were taken only in the upstream section, and keeping the discharge constant we monitored the performance of the acoustic flowmeter simulating the breakdown of any one or two of the four acoustic paths.
In the first set six tests were carried out keeping all the acoustic paths both upstream and downstream active, with an acquisition interval of 20 minutes for each test and a varying discharge between 40 to 100 % of the nominal value. The results displayed in Tab.2 show negligible differences even if integration intervals of the recorded data equal to half and a quarter of the entire recording period are considered. We were therefore able to observe that the corrective value of 1.2% determines differences between the discharges upstream and downstream which remain below 0.35 % even if integration intervals below 8 minutes are considered; this value was introduced as the parameter in the acquisition unit for calculating the discharge.
For the downstream section, the first set of tests revealed disturbing elements in the velocity distribution which were produced by the presence of the 45° curve only two diameters upstream of the flowmeter. Infact the highest velocity values were detected in the lowest part of the section, paths 1 and 2, which is in complete agreement with the flow theory downstream of the curves. This can be seen in Tab. 3 where there is a comparison of the values of the ratios between the velocities of the individual acoustic

paths and the mean velocity, with the theoric value corresponding to the profile of a fully developed flow, which is in compliance with the law of power.

In the second set of tests the system was subjected to stress by simulating a breakdown of the acoustic paths in the downstream section , leaving all the paths upstream active. All possible configurations were considered simulating the breakdown on one or two of the acoustic paths, i.e. the chosen ones, maintaining the discharge flow constant. Altogether 10 tests were carried out, creating different combinations of the supposedly broken acoustic paths, and the results in Tab. 4 reveal that the difference between the upstream and downstream discharges mainly depends on the acquisition range, i.e. on the number of samples the mean is calculated from. Provided that the integration time T was over 240 seconds, we in fact only recorded values below 1% even when only two acoustic paths were active; on the other hand, the difference was greater than 1% but nevertheless remained below 2%, when integration times of 1/4 T were considered. In this second test we also introduced a leak test, estimated in the order of 50 l/s, which was made by diverting water from a spill valve in the valve hall. The results which were obtained by integrating the upstream and downstream discharge values for a time interval of 20 minutes with all the paths active, revealed a difference of 69 l/s, corresponding to 0.5 % of the discharge value observed in the penstock which was 13.5 m^3/s. The difference maintains the same value i.e. it reveals the presence of a leak even with integration times of 10 or 5 minutes.

In the third set of tests the acoustic flowmeter in the upstream section was subjected to stress by simulating in the same way as was done for the downstream section, the breakdown of one or more acoustic paths. The fact that there is a long straight lenght upstream of the section, i.e.15 diameters, meant that it was possible to have a regular distribution of the velocities, which corresponds to a fully developed flow.

Tab.5 gives the discharges that were calculated for the entire acquisition period T and for 1/4 T, as well as the number of active acoustic paths, the difference ε of the discharges calculated for the different configurations, or rather with all four acoustic paths working and with one or two out of operation. In this case the results showed negligible differences of less than 0.5 %, even for integration times below 60 seconds as in the tests which simulated the breakdown of one or two paths.

6. Tests conducted on plant B and results

When the differential protection system was activated, the recording and processing of the discharge values was performed and it revealed significant differences between discharge values in section 1 (the sum of the discharges from penstocks n°1 and n°2) and the corresponding values from the downstream sections.

These differences, which were 1 % lower for penstock n° 3, and 2 % higher for section n°1, required further tests to define the corrective terms to apply in order to make the upstream and downstream discharges the same and to assess the protection system's performance in handling anomalies in the acoustic paths.

Two sets of tests were carried out:

the first set: discharge measuring operations were dealt with separately in penstocks 1 and 2 i.e. the configuration of the system was changed from designed to provisional.

The latter considered section n° 1 as the discharge conveyed by penstock n° 1 and section n° 2 as the discharge conveyed by penstock n° 2, temporarily excluding penstock n° 3 from the measurements.

With this "temporary" configuration, the discharge and velocity values of the single acoustic path were recorded, with the flow at maximum value, initially with all the acoustic paths operating and subsequently with several presumed out of operation. We analyzed the performance of the system by considering one anomaly from only one path for the sections equipped with two acoustic paths and one anomaly of two paths for the monitored sections with four acoustic paths. The same test was then carried out in the second part of the test for penstock n° 3 which was equipped with only two acoustic paths both upstream and downstream.

The results in Tab. 6 suggest that when all the paths are active, the differences between the upstream and downstream discharge are 5 % for penstock n° 1, 1.7 % for penstock n° 2 and 0.9 % for n° 3. However, these differences change when a breakdown occurs in one acoustic path for the sections equipped with two paths and in two for those equipped with four, with differences when all the acoustic paths are working (test n° 1) of 1.4 % for penstock n° 1, 2.6 % for n° 2 and 1.9 % for n° 3.

In the second set of tests we investigated the behaviour of the system with the designed configuration with two discharges: the first is the sum of the flows in penstocks 1 and 2 and the second is the flow in penstock n° 3.

Discharge and velocity values were recorded in all the sections with the group having a variable capacity from 6 to 15 MW with a variable discharge ranging from 40 to 100% of the nominal value and all the acoustic paths operating. The difference between upstream and downstream values remained the same when the discharge changed. Subsequently the flow was kept at a constant value and a breakdown was simulated in only one of the six paths in penstocks 1 and 2.

Based on an analysis of the results, reported in Tab.7 we can ascertain that the breakdown in only one path (the maximum envisaged in this designed configuration) will not modify the differences between the upstream and downstream discharges that were detected when all four acoustic paths were working (test n°1).

This operating condition of the protection system justifies the smaller differences in relation to the first set since the number of out of operation acoustic paths has been reduced and, moreover, the negative errors for penstock 1 and positive ones for penstock n° 2 compensate each other.

In fact in the designed configuration (penstock n°1+penstock n°2) if the system was allowed to operate in the case of contemporary anomalies in two acoustic paths, it would mean losing the discharge of these penstocks entirely since both are equipped with only two paths upstream and downstream.

From an assessment of the first set of tests, a corrective coefficient of the acoustic path weight in penstocks 1 and 2 was calculated for the sections with a temporary configuration, in order to define the unit ratio between the upstream discharge and the downstream one. The correction was operated for both the penstocks on the weight function of the downstream paths which were considered subject to greater disturbed conditions than the paths upstream. We did the same for penstock 3 , in this case correcting the weights of the upstream section since the downstream section is located in a straight lenght which makes it possible to obtain a good distribution of the velocity field. The results are displayed in Tab.8, while Tab.9 gives a comparison of the adimensional velocities recorded by the upstream and downstream paths, with theoric values deduced from the hypothesis of a fully developed flow which agrees with the law of power.

Through the tests it was possible to assess the overall behaviour of the system at maximum capacity with sections equipped with two and four acoustic paths. An analysis of the data appears to show an overestimation of the discharge when two paths and not four are used. In fact a difference of 5 % was recorded for penstock n° 1 and of 1.7 % for n° 2. In the case of penstock n° 3, which was monitored both upstream and downstream, a difference of between 0.8 e 1.1 % was observed when only two paths were in use . For this penstock, in fact, the lowest number of paths were used both upstream and downstream since it presented more regular flow conditions in both sections compared to the other two penstocks.

7. Conclusions

Tests conducted on plant A, which was equipped with four-path acoustic flowmeters in both beginning and end sections, showed that:

- the correction of the discharge difference detected when the system was activated remains constant even when the discharge varies with values ranging from 40 to 100% of the nominal flow.
- the disturbing element of the 45° bend located only 2 diameters upstream of the downstream flowmeter creates an unsymmetrical flow field which is considerably different from a fully developed flow, and this entailed a 1.2 % difference in the discharge measurements from the upstream discharge; this value remained low thanks to the high number of paths used;
- discharge values measured by a flowmeter with four acoustic paths are still reliable, even if one or two of the acoustic paths break down, provided that integration times of over a minute are considered since the system's software handles the relations between the different acoustic path velocities and therefore in the event of a breakdown it is able to reconstruct the velocities of the interrupted acoustic paths;
- the system is even capable of detecting slight water leaks in the order of 0.5-1 % of the nominal discharge, provided that adequate integration intervals are considered i.e. at least 5-minute intervals;
- it was seen that the integration time is actually more important than the number of acoustic paths in operation, at least up to a minimum of two;

Tests conducted on plant B confirmed the results obtained in plant A with a few additional considerations:

- in sufficiently regular flow conditions, the difference between upstream and downstream discharges was within 1 % , even when flowmeters were equipped with only two paths; on the other hand, in disturbed conditions with considerably lower distances from the acoustic flowmeters than the ones prescribed in IEC, the differences between upstream and downstream discharges reached values ranging between 2 and 5 %, even when two or four-path acoustic flowmeters were used. In the latter case, the difference between upstream and downstream discharges is also affected by the number of active acoustic paths used, since the breakdown of one path in the case of two-path flowmeters, or two in the case of four-path flowmeters introduces a discharge variation and therefore a fictitious loss.

An analysis of the tests carried out separately on each of the three penstocks made it possible to define new weights for each acoustic path and to reduce the difference between the upstream and downstream discharges to less than 0.5%.

In conclusion we would like to stress the importance of using reliable equipment, resorting to systems that have at least two acoustic paths since if a single-path system is used, a breakdown could actually occur in a transducer and this would disactivate the protection system.

8. Bibliography

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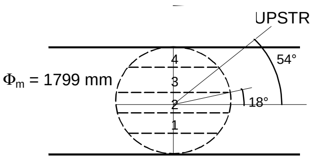
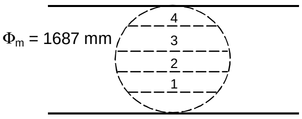
UPSTREAM



Path	L [mm]	θ
1	1387	45°06'03"
2	2353	45°15'15"
3	2354	45°12'28"
4	1391	45°15'34"

DOWNSTREAM

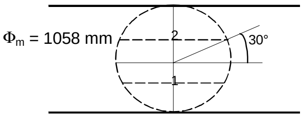


Path	L [mm]	θ
1	1351	43°28'41"
2	2171	45°50'39"
3	2171	45°52'03"
4	1344	43°06'13"

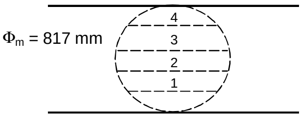
Fig. 3 - Hydroelectric power plant A - Differential protection of the penstock - Geometric characteristic of the acoustic flowmeter

Penstock n° UPSTREAM DOWNSTREAM

1

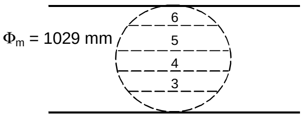


Path	L [mm]	θ
1	1112	51°25'24"
2	1114	51°24'43"

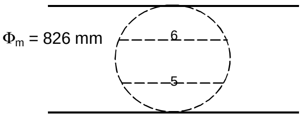


Path	L [mm]	θ
1	575	45°38'57"
2	1030	45°04'51"
3	1032	45°05'27"
4	572	45°19'33"

2

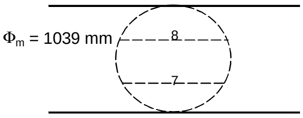


Path	L [mm]	θ
3	742	44°42'02"
4	1312	44°52'21"
5	1315	45°02'10"
6	748	45°17'18"

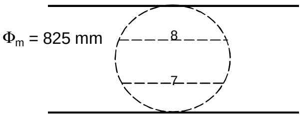


Path	L [mm]	θ
5	1371	29°02'33"
6	1372	29°07'02"

3



Path	L [mm]	θ
7	1089	51°20'17"
8	1091	51°24'24"



Path	L [mm]	θ
7	1370	29°12'17"
8	1372	29°16'18"

Fig. 4 - Hydroelectric power plant B - Differential protection of the penstocks - Geometric characteristic of the acoustic flowmeter

Tab.1 - Hydroelectric power plant A and B
Differential protection system of the penstocks
Characteristics of the disturbing elements

Plant	**Penstock**	**Section**	**Path**	**Disturbance type**		**Diameters number**	
	(n°)		(n°)	Upstream	Downstream	Upstream	Downstream
A	1	upstream	4	section change	butterfly valve	15	18
		downstream	4	45° bend	T biforcation	2	1
B	1	upstream	2	intake	butterfly valve	7,3	3,6
		downstream	4	45° bend	T inlet	34	1
	2	upstream	4	butterfly valve	26° bend	4,5	4,3
		downstream	2	45° bend	T biforcation	34	1
	3	upstream	2	intake	butterfly valve	9,3	1,9
		downstream	2	45° bend	90° bend	45	>3

Tab. 2 - Power plant A - Difference (%) between upstream and downstream discha
for all the paths well running with different discharges and integration time

Integration time (minutes)	Upstream discharge (m^3/s)					
	6.749	7.977	9.978	13.091	13.600	15.889
	(%)	(%)	(%)	(%)	(%)	(%)
20	0.07	0.13	0.19	0.03	-0.13	-0.01
10	0.00	0.14	0.26	-0.02	-0.09	-0.14
10	0.13	0.11	-0.14	0.09	-0.16	0.12
5	0.27	-0.05	0.23	0.00	-0.04	-0.31
5	-0.26	0.34	0.26	-0.05	-0.15	0.04
5	0.22	0.20	-0.03	-0.01	-0.10	0.09
5	0.05	0.02	-0.26	0.20	-0.23	0.16

Tab. 3 - Power plant A - Downstream acoustic flowmeter - Velocity values at each acoustic path
and ratio between the velocity and the mean velocity of the section

Run (n°)	Q (m^3/s)	V_m (m/s)	V_1 (m/s)	V_2 (m/s)	V_3 (m/s)	V_4 (m/s)	X_1	X_2	X_3	X_4
1	6.749	3.020	3.299	3.309	2.698	2.492	1.092	1.096	0.893	0.825
2	7.977	3.569	3.909	3.910	3.190	2.952	1.095	1.096	0.894	0.827
3	9.978	4.465	4.889	4.888	3.993	3.702	1.095	1.095	0.894	0.829
4	13.091	5.857	6.369	6.401	5.244	4.871	1.087	1.093	0.895	0.832
5	13.600	6.085	6.620	6.633	5.447	5.035	1.088	1.090	0.895	0.827
6	15.889	7.109	7.721	7.761	6.365	5.919	1.086	1.092	0.895	0.833
						mean	1.091	1.093	0.895	0.829
				theoric value			**0.888**	**1.045**	**1.045**	**0.888**

$X_1=V_1/V_m$ $X_2=V_2/V_m$ $X_3=V_3/V_m$ $X_4=V_4/V_m$

Tab. 4 - Power plant A - Difference between upstream and downstream discharg for anomalies of one or two acoustic paths at the downstream flowmeter

Run (n°)	Integration time (s)	Upstream discharge (m^3/s)	Acoustic path well running	ε (%)	1/4 of the integration time (s)	ε_{max} (%)
1A	240	13.282	1,2,3,4	0.33	60	0.74
1B	360	13.341	1,2, ,4	-0.60	90	-1.81
2A	240	13.392	1,2,3,4	0.09	60	0.69
2B	360	13.314	1,2,3,	-0.22	90	-0.50
3A	180	13.243	1,2,3,4	0.12	45	0.51
3B	240	13.254	,2 3,4	-0.16	60	-0.35
4A	154	13.351	1,2,3,4	0.14	39	0.30
4B	264	13.301	1, ,3,4	0.19	66	0.52
5A	249	13.388	1,2,3,4	-0.06	62	-0.44
5B	251	13.379	, ,3,4	0.44	63	1.59
6A	180	13.37	1,2,3,4	0.08	45	0.58
6B	266	13.335	,2, 4	0.09	67	0.95
7A	167	13.39	1,2,3,4	0.05	42	-0.34
7B	233	13.379	,2,3,	0.16	58	0.46
8A	134	13.467	1,2,3,4	-0.49	34	-1.15
8B	233	13.427	1, , ,4	0.06	58	-0.59
9A	275	13.515	1,2,3,4	-0.14	69	-0.42
9B	240	13.451	1, , 3,	0.88	60	1.53
10A	156	13.449	1,2,3,4	-0.12	39	-0.35
10B	249	13.364	1,2, ,	-0.63	62	-1.30

$\varepsilon = (Q_{downstream} - Q_{upstream})/Q_{upstream} * 100$

Tab. 5 - Power plant A - Upstream acoustic flowmeter - Difference between measured discharge with all the paths well running and with anomalies on one or two paths

Run (n°)	Integration time (s)	Discharge (m^3/s)	Path well running (n°)	ε (%)	1/4 of the integration time (s)	Discharge (m^3/s)	ε (%)
1A	154	14.527	1,2,3,4		39	14.541	
1B	156	14.494	,2,3,4	-0.23	39	14.510	-0.21
2A	168	14.544	1,2,3,4		42	14.487	
2B	144	14.551	1, ,3,4	0.05	36	14.545	0.40
3A	179	14.554	1,2,3,4		45	14.528	
3B	135	14.529	1,2, ,4	-0.17	34	14.515	-0.09
4A	232	14.290	1,2,3,4		58	14.299	
4B	299	14.313	, ,3,4	0.16	75	14.316	0.12
5A	286	14.282	1,2,3,4		72	14.290	
5B	266	14.351	,2, ,4	0.48	67	14.343	0.37
6A	257	14.313	1,2,3,4		64	14.324	
6B	259	14.349	,2,3,	0.25	65	14.335	0.08
7A	281	14.347	1,2,3,4		70	14.347	
7B	287	14.293	1, , ,4	-0.38	72	14.326	-0.15

$\varepsilon = (Q_{wih\ anomalies} - Q_{withuot\ anomalies})/Q_{without\ anomalies} * 100$

Tab. 6 - Power pant B - Differential protection system of the penstock

Test of the acoustic flowmeter's performances

Penstock	Run	Qupstream	Path		Qdownstream	Path				ε 1)
(n°)	(n°)	(m^3/s)	1	2	(m^3/s)	1	2	3	4	(%)
1	1	1.311	A	A	1.245	A	A	A	A	-5.0
	2	1.304	A	N.A.	1.145	A	A	A	A	-4.5
	3	1.301	A	A	1.254	A	A	N.A.	N.A.	-3.6
	4	1.303	A	A	1.251	N.A.	A	A	N.A.	-4.0
	5	1.308	A	A	1.247	A	N.A.	N.A.	A	-4.7

Penstock	Run	Qupstream	Path				Qdownstream	Path		ε 1)
(n°)	(n°)	(m^3/s)	3	4	5	6	(m^3/s)	5	6	(%)
2	1	1.175	A	A	A	A	1.195	A	A	1.7
	2	1.179	A	A	A	A	1.200	A	N.A.	1.8
	3	1.185	A	A	N.A.	N.A.	1.199	A	A	1.2
	4	1.182	N.A.	A	A	N.A.	1.202	A	A	1.7
	5	1.213	A	N.A.	N.A.	A	1.202	A	A	-0.9

Penstock	Run	Qupstream	Path		Qdownstream	Path				ε 1)
(n°)	(n°)	(m^3/s)	7	8	(m^3/s)	7	8			(%)
3	1	1.367	A	A	1.355	A	A			-0.9
	2	1.367	A	A	1.350	A	N.A.			-1.2
	3	1.388	A	N.A.	1.356	A	A			-2.3
	4	1.345	N.A.	A	1.358	A	A			1.0
	5	1.371	A	A	1.356	A	N.A.			-1.1

1) $\varepsilon = (Q_{downstream} - Q_{upstream})/Q_{upstream} * 100$

A = Active path (well running) N.A.= Not active path

Tab. 7 - Power plant B - Differential protection system of the penstocks

Test of the acoustic flowmeter performances in standard configuration

Penstock	Run	Qupstream	Path						Qdownstream	Path						ε 1)
(n°)	(n°)	(m^3/s)	1	2	3	4	5	6	(m^3/s)	1	2	3	4	5	6	(%)
1+2	1	2.492	A	A	A	A	A	A	2.449	A	A	A	A	A	A	1.8
	2	2.496	N.A.	A	A	A	A	A	2.450	A	A	A	A	A	A	1.9
	3	2.494	A	A	N.A.	A	A	A	2.450	A	A	A	A	A	A	1.8
	4	2.498	A	A	A	N.A.	A	A	2.454	A	A	A	A	A	A	1.8
	5	2.497	A	A	A	A	A	A	2.452	N.A.	A	A	A	A	A	1.8
	6	2.502	A	A	A	A	A	A	2.458	A	N.A.	A	A	A	A	1.8
	7	2.495	A	A	A	A	A	A	2.449	A	A	A	A	N.A.	A	1.9

1) $\varepsilon = (Q_{upstream} - Q_{downstream})/Q_{downstream} * 100$

A = Active path (well running) N.A.= Not active path

Tab. 8 - Power plant B - Differential protection system of the penstocks

New weight parameters for each acoustic path

Upstream flowmeter					Downstream flowmeter				
Penstock	Acoustic	Weight parameter			Penstock	Acoustic	Weight parameter		
	path	Designed	Proposed	Difference		path	Designed	Proposed	Difference
(n°)	(n°)			(%)	(n°)	(n°)			(%)
	1	0.2569	0.2569	0		1	0.0683	0.0721	5.6
1									
	2	0.2569	0.2569	0		2	0.1789	0.1888	5.5
					1				
	3	0.0672	0.0672	0		3	0.1789	0.1888	5.5
	4	0.1759	0.1759	0		4	0.0683	0.0721	5.6
2									
	5	0.1759	0.1759	0		5	0.2527	0.2489	-1.5
					2				
	6	0.0672	0.0672	0		6	0.2527	0.2489	-1.5
	7	0.5000	0.4957	-0.86		7	0.5000	0.5000	0.0
3					3				
	8	0.5000	0.4957	-0.86		8	0.5000	0.5000	0.0

Tab. 9 - Power plant B - Differential protection system of the penstocks

Comparison between adimensional velocities at the acoustic paths

Upstream flowmeter					Downstream flowmeter				
Penstock	Path	V_i/V_m		Difference 1)	Penstock	Path	V_i/V_m		Difference 1)
(n°)	(n°)	Measured	Theoric	(%)	(n°)	(n°)	Measured	Theoric	(%)
	1	1.031	1.000	3.1		1	0.886	0.888	-0.2
1									
	2	0.969	1.000	-3.1		2	1.100	1.045	5.3
					1				
	3	0.962	0.888	8.4		3	1.025	1.045	-1.9
	4	1.116	1.045	6.8		4	0.787	0.888	-11.4
2									
	5	0.988	1.045	-5.5		5	1.044	1.000	4.4
					2				
	6	0.768	0.888	-13.5		6	0.956	1.000	-4.4
	7	1.0350	1.000	3.5		7	1.023	1.000	2.3
3					3				
	8	0.9650	1.000	-3.5		8	0.977	1.000	-2.3

1) Difference =($(V_i/V_m)_{measured}$ - $(V_i/V_m)_{theoric}$) / $(V_i/V_m)_{theoric}$ *100