SIMPLIFIED CURRENT METER MEASUREMENTS USED TO VERIFY IMPROVEMENT OF TURBINE EFFICIENCY AFTER RUNNER REPLACEMENT

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SUMMARY

An 8.5 MW Francis turbine with 21 m head from 1925 has recently been equipped with a runner of new design. Complete current meter measurements were previously made in 1925 and in 1957 in the pressure conduit, with an array of 81 current meter positions. Thus, the velocity profile as a function of discharge was well known from the old report. Related to the installation of the new runner, new current meter tests have been made. It was decided to use a simplified current meter measurement, where only 7 current meters were installed on a fixed horizontal beam. The correlation between average velocity of these 7 current meters and the total discharge was found from the data in the report from the 1957 current meter measurements. Such simplified measurements were done before and after runner replacement. Even if the uncertainty in absolute efficiency is increased because of the reduced number of velocity measurements, the repeatability of the test is good. The improvement in performance of the new runner could therefore be measured with acceptable accuracy. The simplified method of measurement for verification of the guaranteed efficiency was accepted by the turbine supplier.

1 DESCRIPTION OF PLANT, UNITS AND HISTORY

Solbergfoss dam and power plant is located east of Oslo in Norway's largest river, Glomma. It consists of a concrete gravity dam and two power houses with a head of about 20 m. The old power house, Solbergfoss 1, was built from 1917 to 1924, and contains 13 Francis units (12 of 8.5 MW and one of 12,5 MW) commissioned between 1924 and 1959. A new underground powerhouse, Solbergfoss 2, with one large Kaplan unit (100 MW) was commissioned in 1985.

This paper concerns unit no. 9 in the old power house. Figure 1 shows a top view of the dam and the old powerhouse. The river is lead into a forebay alongside the power house, and the discharge leaving the turbines enters a tailwater canal in the riverbed. Figure 2 shows a cross-sectional view of a unit and its water passage from intake to tailwater. About half way into the pressure conduit, guide slots for a current meter frame are arranged. All the 13 water passages are built according to the same drawing, which means that the differences are only building tolerances.

2 PREVIOUS TURBINE EFFICIENCY MEASUREMENTS

In 1997, all previous measurements at Solbergfoss I were summarized by Berdal Strømme [2]. Turbine efficiency measurements with current meters had been performed on all units during commissioning. Unit 9 was measured in 1925. Documentation of this test has not been found. The unit was measured again in 1957. This test was documented by Thoresen and Hansen [3], and contains complete tables of all flow velocities and measured values. In the same period, guarantee measurements using current meters were performed on unit 10. This test, for which the current-meter setup was identical to the test of unit 9, is reported by Neyrpic [4], and contains an evaluation of the test accuracy.

According to Thoresen and Hansen, the efficiency test of unit 9 took two days, but it is probable that the installation and deinstallation of equipment is not included. In the report of Neyrpic, the complete efficiency test of unit 10 took seven days.

3 CONDITION ASSESSMENT IN 1997

In 1997, the power company wanted to make turbine efficiency tests of the units in the old power house. The power station had so far been operated manually, but now a computerised plant control system was installed, and efficiency curves for the control system were needed. The primary goal for the measurements was to find the shape, and more specifically the peak, of the efficiency curve, in order to optimise power generation. The secondary goal was to establish an approximate absolute efficiency level. Complete current meter measurements were considered to be too expensive. Therefore, it was proposed to perform simplified current meter measurements together with Winter - Kennedy measurements on three units (no. 3, 5 and 9). As the units did not have pressure taps for Winter-Kennedy measurements, identical tap arrangements were installed in the turbine spiral cases of all of the units.

Simplified current meter measurements were made, which showed good agreement between current-meter measurements and Winter-Kennedy measurements. Therefore, Winter-Kennedy measurements were performed on the rest of the units.

The resulting efficiency curves from these measurements have since 1997 been used in the optimisation of the plant operation.

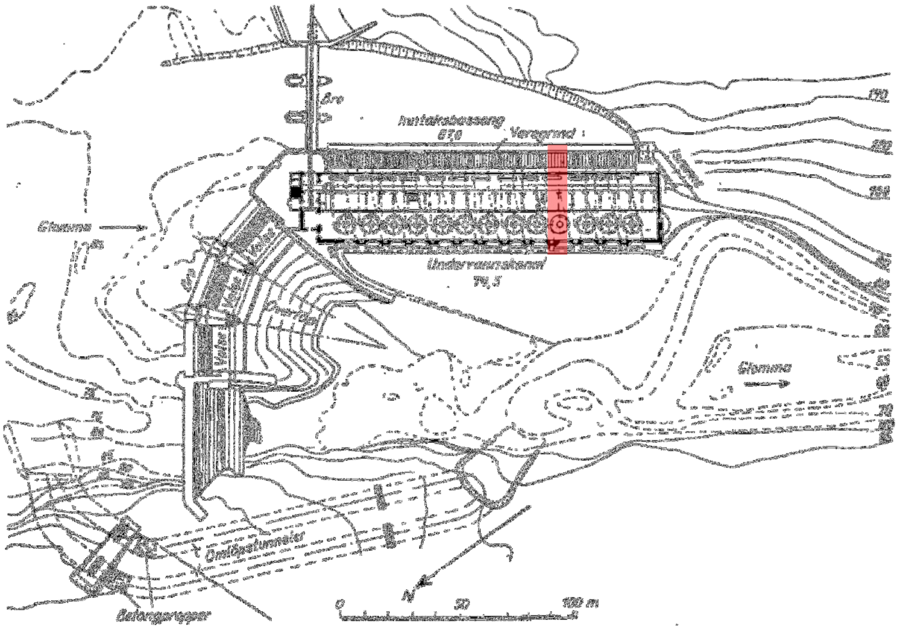
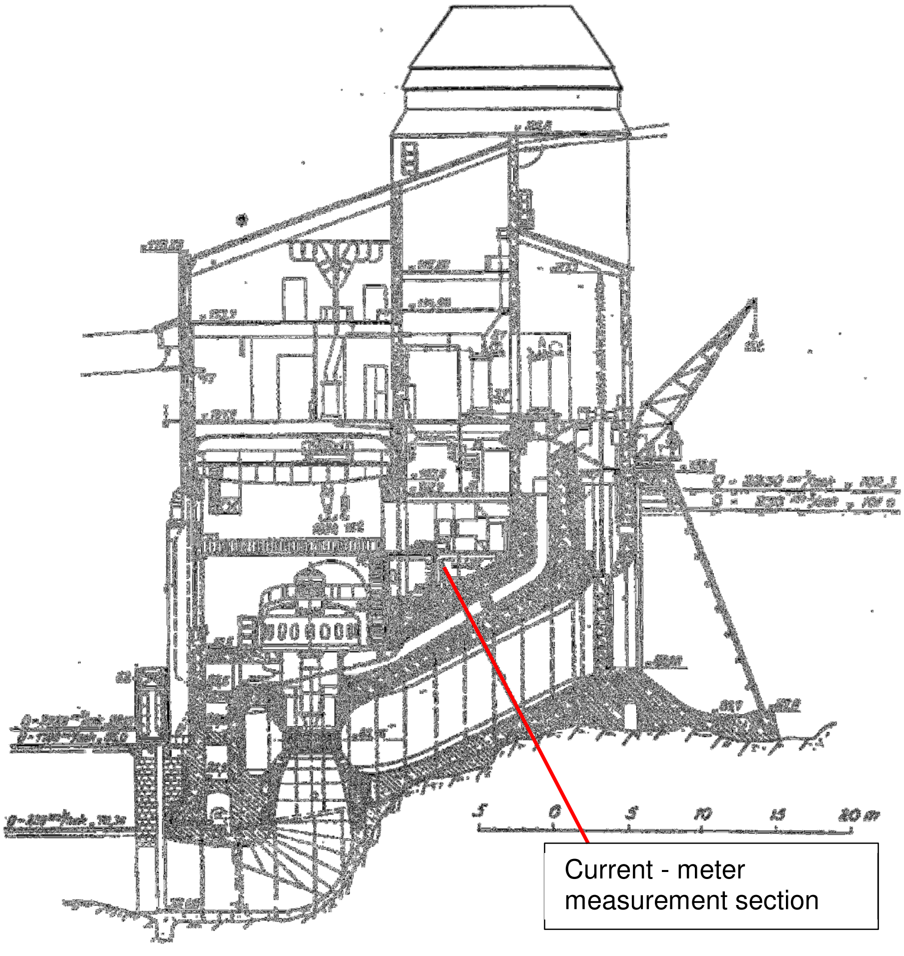


Figure 1 Solbergfoss I - top view. Unit 9 is marked in red. Reference: Norske kraftverker [1]



Current - meter measurement section

Figure 2 Cross-section of Solbergfoss I power-house. Reference: Norske kraftverker [1]

4 SIMPLIFIED CURRENT-METER SETUP

The concept of simplified current-meter measurements was concieved from an analysis of the previous current meter measurements reported by Thoresen and Nybro Hansen [3] and Neyrpic [4]. The full current meter measurements used a current meter beam with 9 current meters that were positioned in 9 levels. A total of 81 velocities were recorded to determine the turbine discharge, as seen in Figure 3. The measurements show that the velocity profile is even and symmetrical, which is due to the straight inflow conduit.

The velocity profiles at various discharges were analysed, and the 3rd level from the bottom was selected as a reference level (marked in red in Figure 3). Table 1 shows the measured velocities in the selected level for all test points. As is shown in Table 2, the ratio between the average measured velocity of the current meters in the selected level and the flow calculated using all 81 current-meter velocities ($\mathbf{k}_{v9}$ and $\mathbf{k}_{v7}$) was almost constant. Also, it was found that not using the two current meters closest to the left and right conduit walls would not significantly affect the accuracy of the established correlation. The conclusion of these findings was that a fairly accurate discharge measurement could be made with 7 current meters installed on a fixed horizontal beam in the reference position. The simplified arrangement of the current meters is shown in Figure 4.

Table 1 Flow velocities in 3rd leel from bottom, from current-meter measurements of unit 9 in 1957 [3]

Test no.	Velocity (m/s) in position number								
	1	2	3	4	5	6	7	8	9
I	0.960	0.950	1.009	1.061	1.001	0.990	0.992	0.948	0.848
II	1.131	1.235	1.163	1.247	1.192	1.194	1.189	1.155	0.993
III	1.256	1.290	1.302	1.388	1.297	1.296	1.309	1.209	1.103
IV	1.292	1.231	1.393	1.454	1.312	1.345	1.359	1.257	1.112
V	1.361	1.315	1.475	1.535	1.417	1.530	1.444	1.364	1.158
VI	1.340	1.372	1.533	1.555	1.462	1.483	1.491	1.427	1.216
VII	1.545	1.525	1.587	1.675	1.546	1.568	1.567	1.524	1.286
VIII	1.237	1.175	1.388	1.429	1.341	1.373	1.366	1.312	1.123
IX	1.177	1.180	1.343	1.414	1.292	1.365	1.321	1.262	1.086

Table 2 Calculated flow from current-meter measurements of unit 9 in 1956 [3], and calculated velocity coefficients for 9 and 7 current meters respectively

			9 current meters		7 current meters	
Test no.	calculated flow m^3/s	flow per area m/s	average meas. velocity m/s	velocity coeff. $\mathbf{k}_{V9}$ -	average meas. velocity m/s	velocity coeff. $\mathbf{k}_{V7}$ -
I	30.55	0.953	0.973	0.979	0.993	0.959
II	36.68	1.144	1.167	0.981	1.196	0.956
III	41.00	1.279	1.272	1.005	1.299	0.985
IV	41.40	1.291	1.306	0.988	1.336	0.966
V	44.05	1.374	1.400	0.981	1.440	0.954
VI	45.75	1.427	1.431	0.997	1.475	0.967
VII	47.95	1.495	1.536	0.974	1.570	0.952
VIII	41.58	1.297	1.305	0.994	1.341	0.967
IX	40.15	1.252	1.271	0.985	1.311	0.955
Average				0.9871		0.9625
Standard deviation				0.0100		0.0102

The simplified method depends on that the velocity profile does not change between the tests. The tests in 1957 were done during winter time when the river flow typically is kept quite constant, and well below the total capacity of the power station. Thus, the velocities in the forebay were moderate. For subsequent measurements, in 1997, 2011 and 2012, similar conditions were established by regulating most of the flow through the new underground power house of Solbergfoss II.

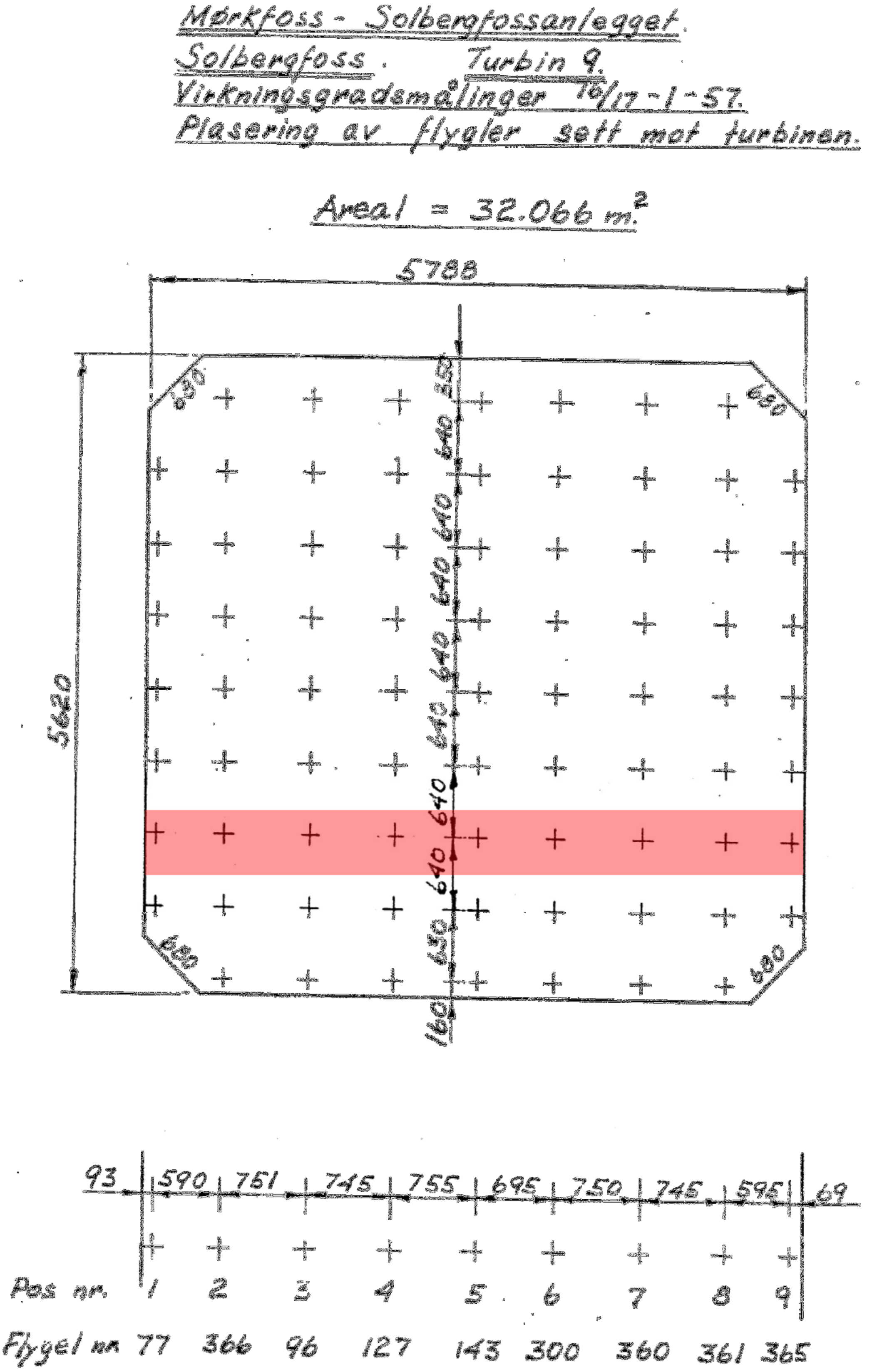


Figure 3 Array of 81 positions for complete current-meter flow velocity measurements. The position used for simplified measurements is indicated in red.

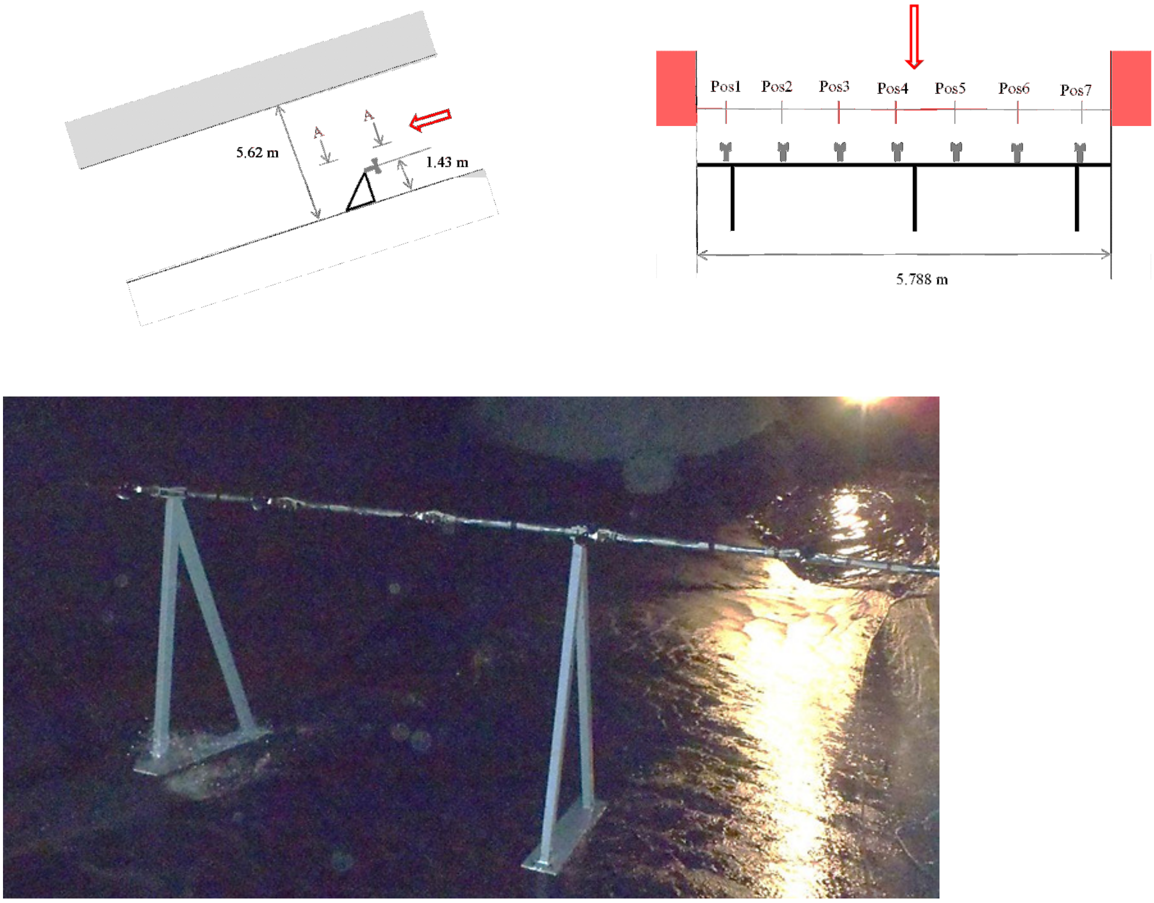


Figure 4 Arrangement of 7 current-meters in one fixed horizontal position for simplified measurements

5 UNCERTAINTY OF THE SIMPLIFIED MEASUREMENTS

The uncertainty in the absolute turbine efficiency based on the performed measurements is mainly determined by the uncertainty in the flow measurements. Neyrpic [4] presents an uncertainty analysis of the measurements of unit 10 in 1957, in which the random and systematic uncertainties in flow are ±0.33% and ±0.95 % respectively. The total uncertainty in flow is then ±1.0 %. Since the measurements of unit 9 and unit 10 were done at the same time, with the same equipment and same setup, the same uncertainty in flow in the measurement of unit 9 may be assumed.

For the simplified measurements, the additional uncertainty compared to complete measurements is related to the velocity coefficient $\mathbf{k}_{v7}$. The standard deviation in the velocity coefficient is 1%, as presented in Table 2. For a 95 % confidence interval, the uncertainty in the velocity coefficient is ±2%, and the total uncertainty in flow is ±2.2%.

However, the uncertainty is smaller when comparing different tests done with the same, simplified flow measurement setup.

6 PROCESS LEADING TO A CONTRACT ON RUNNER RENEWAL

The units are mechanically robust, and had little sign of wear. Therefore, it was the relatively poor hydraulic performance found in 1997 which was the main driver for investigating the benefits of a replacement runner with a modern design. It was found that an improvement of efficiency, and an increase in the maximum power output within the 10 MVA limit of the generator together would make a replacement runner profitable.

In addition, the Norwegian government has introduced a system of economic stimulation to power companies to increase the generation of renewable energy - either by upgrading existing facilities or by building new units. The system of economic benefits, which is labelled green certificates, was not an important issue for the replacement runner project, but will become a bonus on top of existing revenues. The green certificates were introduced in 2012 - the application for certificates for unit 9 is being written, but has not at the time of publication of this paper been sent or approved.

It was decided to replace the runners in three units, replacing one runner each year starting in 2011/2012. Unit 9 was to have the first replacement runner. A request for quotation on new runner was sent out, and the Norwegian turbine manufacturer Rainpower was awarded the contract. The contract of the two subsequent runners could be altered or cancelled based on the performance of the first runner. As a basis for the performance guarantees, Rainpower was informed of the results of the simplified turbine efficiency measurements in 1997. It was agreed between E-Co and Rainpower that simplified current-meter measurements would be used to validate the efficiency guarantees of the new runners, even though the method does not comply to IEC 60041 [5]. The main deviation from the standard is the number of measurement points - the standard requires more than 25 velocity measurement points.

7 NEW RUNNER DESIGN

Designing a new runner for the existing turbine at Solbergfoss I provided several challenges. The power plant has low head and high discharge, and is better suited for a Kaplan turbine than a Francis turbine. The turbines have a specific speed, nq_{rpm}, above 100. The new runner was to increase the existing power output by more than 20%, and operate within a large head variation (Hmax/Hmin=2) without cavitation and with good stability behaviour. In addition, the run-away speed of the new runner was limited by the generator, and the runner had to fit into the existing turbine casing without any modifications to the surrounding parts.

Normally, the starting point when designing a new runner is a well documented and similar reference model turbine which can be used for validation and comparison. During the last few years, Rainpower has developed a new generation of medium/low head Francis turbines called Rainpower Storm. Several model turbines have been developed and tested. However, none of these models have specific speeds which are in the range of Solbergfoss I. It was therefore necessary to design the new runner relying mainly on CFD results.

The design process took about two months. More than 50 different runner designs were made and tested with CFD, before the final design was ready for production. The hub, band and blades, which were made of carbon steel, were produced in China, and were welded together and painted at Rainpower's workshop at Sørumsand, Norway.

The new runner has a design which differs significantly from the old runner. Most noticeably is the increased thickness at the inlet of the vanes which increase the performance at low heads and ensures a cavitation-free inlet. The inlet edge has also been skewed to provide a better pressure distribution at the runner inlet. Secondly, the number of blades has been reduced from 14 to 13 to reduce friction losses. Several other design choices have also been made to ensure the performance of the new runner.

8 GUARANTEE MEASUREMENTS USING SIMPLIFIED CURRENT-METER MEASUREMENTS

In October 2011 a simplified efficiency test was performed before the unit was stopped for runner replacement. The result of the test was to be used as a basis for evaluation of the performance improvement of the new runner.

In May 2012, a simplified efficiency test was performed after the replacement runner was installed. Winter-Kennedy differential pressure was measured simultaneously. The test took two and a half days - one day of installation, one day of testing, and half a day of de-installation. The test conditions were good - the water levels and generator output were very stable during the tests.

The results of the two measurements are presented in Figure 5. The design head for the new runner is 21 m. The pre-test was done at Hn = 20.0 m and the guarantee test with Hn = 19.3 m. In the figure, all test results are referenced to a net head of Hn = 19.6 m, which was the mean net head between the October 2011 and May 2012 tests. The efficiency has not been corrected, as the measured net heads are within ± 2% of the reference net head. The expected efficiency curve at 19.6 m is calculated by the turbine supplier. The efficiency is presented as relative efficiency, where the highest measured efficiency of the current-meter tests is set to 100%, and all the other test points are scaled accordingly.

Six points may be highlighted:

1. In the May 2012 test, the test point at 8.65 MW was repeated at the end of the test - the deviation in efficiency is only 0.01 percentage points, which indicates a good repeatability.
2. The net increase in turbine efficiency due to the installation of a new runner is about 3.2 percentage points at peak efficiency.
3. The peak efficiency is shifted towards higher load, from 7.1 MW to 8.9 MW.
4. The Winter Kennedy index efficiency is calibrated with the flow measurements. The Winter Kennedy index efficiency is within ± 1% of the current-meter efficiency.
5. The turbine power at the measured peak efficiency is about 0.4 MW higher than what has been calculated by the supplier.
6. The level of measured efficiency in the best efficiency point slightly exceeds the calculated values. The efficiency guaranteed in the contract is given as two weighted points at Hn = 21m, and is not presented here. For comparison with the guaranteed values, the efficiency and flow were referenced to Hn = 21m using the lines of constant opening in the runner hill chart. The conclusion of the measurement is that the guarantee in turbine efficiency is met.

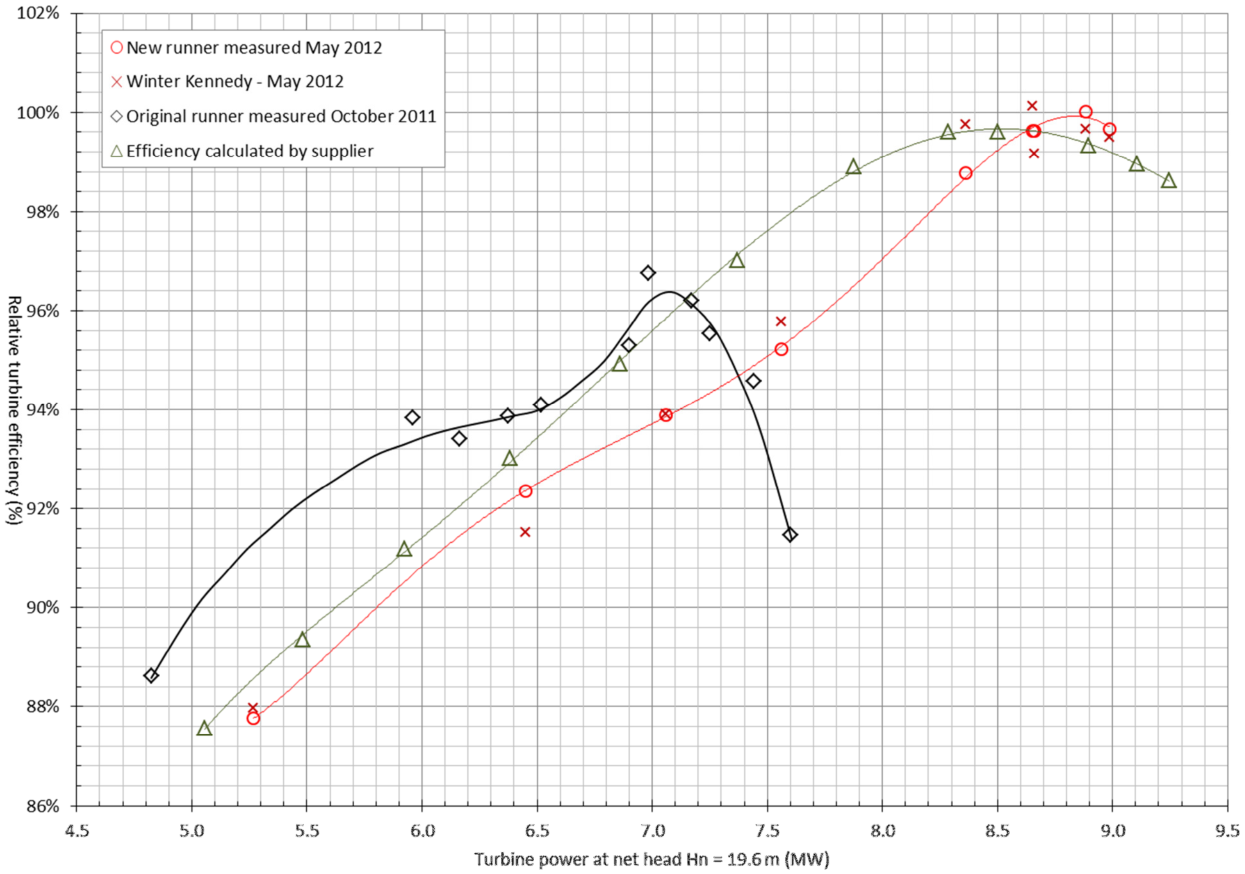


Figure 5 Results of simplified current-meter tests of unit 9 at Solbergfoss I. The efficiency is given as index efficiency, where the highest measured efficiency of the current-meter tests is set to 100%.

9 CONCLUSIONS

The simplified current meter measurements have been successful. The uncertainty in discharge of these simplified measurements is ±2.2%, based on an analysis of complete measurements in the same measurement section. The absolute accuracy is reduced compared to complete measurements, but the repeatability between the tests of the same setup is significantly better than ±2.2%.

The turbine supplier accepted the simplified measurements for verification of turbine efficiency of the new runner.

Installation of a new runner has increased the peak efficiency by 3.2 percentage points, and has increased the maximum power output 18% at Hn = 19.6 m head.

For the power company, the important operating range is between the efficiency peak and maximum output. The measured peak efficiency was closer to the maximum output than what was specified in the contract, but this has actually proved to be beneficial to the power company, given that there are a total of 14 units in the the Solbergfoss power stations in which to optimally distribute the load.

10 REFERENCES

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