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INDEX TESTS OF A FRANCIS UNIT USING THE SLIDING GATE METHOD

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Abstract

The paper focuses on the comparison of index measurements of a Francis turbine with steady state measuring points and measurements under quasi-steady conditions. This second method is called “sliding gate method” and was introduced by Almquist [2]. It is shown that in spite of large fluctuations of the data an excellent repeatability of the curves and perfect agreement with the steady state measurements can be achieved.
These measurements have been performed twice, since the Kraftwerke Zervreila AG wanted to quantify the effects of their repair works on the efficiency level. Efficiency differences of 2.3% at partial load and 1.8% at full load were found. This improvement is mainly due to the reduction of the leakage flow (revision of labyrinth seal).
During both tests, before and after maintenance, the results of the trends from the sliding gate method agree perfectly with the steady state point efficiencies. The result of the sliding gate method is a continuous efficiency curve instead of an approximation curve through discrete points, thus more information on efficiencies in the entire operating range can be acquired. The sliding gate method can significantly reduce the time required to perform an index test.

1 Francis unit in the HPP Safien Platz

Two Francis units with vertical shaft are installed in the hydro power plant of Safien Platz of the Kraftwerke Zervreila AG, Switzerland. The technical specifications of each machine group are:

Name	Value
Rated power	43 MW
Rated discharge	11.5 m^3/s
Rated speed	750 rpm
Specified head	408 m
Turbine elevation	1290.50 m ASL
Runner diameter	1.654 m

Tab. 1: Technical specifications

Fig. 1: Vertical shaft and guide vane apparatus of the Francis unit 1 at HPP Safien Platz

2 Measurement task

In the summer of 2007 the Kraftwerke Zervreila AG carried out maintenance in the HPP Safien Platz on Francis unit 1. The maintenance involved the following works:

- coating of guide vanes and runner
- revision of the labyrinth seal

It was decided to perform index tests before and after maintenance. The Lucerne University of Applied Sciences and Arts (LUASA) was commissioned to carry out these measurements. The aim was to quantify the effects of the maintenance on the efficiency level. In long terms it was of interest to acquire information for better planning of maintenance or rehabilitation intervals.

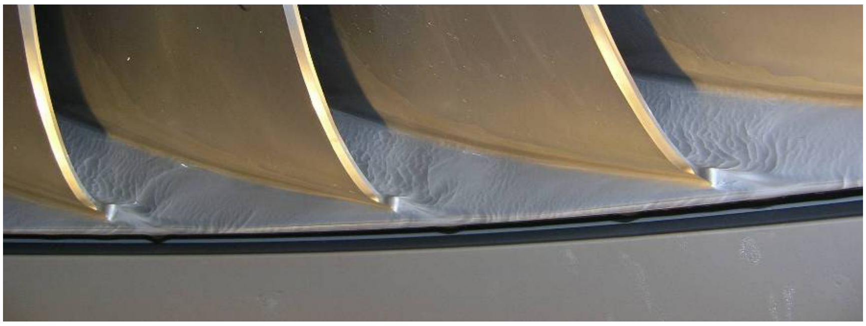

Fig. 3: Erosion damages at the band of the Francis turbine

Fig. 2: Erosion damages on the facing plates of the guide vanes

The runners of the HPP Safien Platz were in operation for about 12 years without major maintenance, that is since 1995. Erosion damages demanded then repair. On the one hand there were sand erosion damages on the facing plates of the guide vanes (Figure 2) and on the other hand on the runner band of the Francis runner (Figure 3). Furthermore the clearance of the labyrinth seal, continuously monitored since 1995, was considerably enlarged by erosion. The large clearance increased leakage and caused an efficiency reduction. It was decided to coat the elements after repair in order to reduce future sand erosion, in spite of the higher friction losses which have to be expected after coating.

3 Index test

To quantify the relative efficiency, index measurements were carried out in accordance with IEC 60041, section 15 [1]. Index measurements give only relative values of discharge and efficiency and are considered as secondary methods. The index test can be a part of a field acceptance test for instance if the primary method shows excessive uncertainties or fails in a certain operating range. Generally, an index test makes sense for a comparison, e.g. a comparison of old and refurbished runners. The measured efficiency increase allows to quantify the return on invest on efficiency level after modifications of runners, casings or internals. A comparison in index efficiency levels is sufficient in these cases. Essential, however, is a sufficient repeatability of the measurements. This requires that no other modifications, e.g. new coats of paint, are done especially in the section where index discharge measurement is carried out

For the tests in HPP Safien Platz the guide vane apparatus was set to a corresponding power output of the generator. After stabilization of the operating point, data acquisition was started. A survey of the surge tank oscillation before the measurements indicated a period time of around 5 minutes. Therefore a measuring duration of 10 minutes was chosen to average the data during two periods of the surge tank oscillation. The sampling rate for data acquisition during the index tests was 0.5Hz.

The index efficiency is defined as follows

$$\eta_{\text{Index}} = \frac{P_T}{\rho \cdot g \cdot H \cdot Q_{Ve}} \qquad (1)$$

where ρ is the density of water, g is the acceleration of gravity.

P_T, the turbine power output, is determined from

$$P_T = \frac{P_{Gen}}{\eta_{Gen}} + P_{VSL} \tag{2}$$

where P_{Gen} is the active power output of the generator, η_{Gen} the generator efficiency and P_{VSL} the thrust bearing loss.
The net head is defined as follows

$$H = \frac{p_{1'} - p_{2'}}{g \cdot \rho} + Z + \frac{v_1^{\ 2} - v_2^{\ 2}}{g \cdot 2} \tag{3}$$

where $p_{1'}$ and $p_{2'}$ are the measured hydrostatic pressures at the high and low pressure measuring sections, v_1 and v_2 are the mean velocities, Z is the altitude correction of the differences between pressure transducers and corresponding measuring section.
For flow rate determination the following formula was used

$$Q_{Ve} = 15.44620 \cdot dp_{Ve}^{\ 0.49006} \tag{4}$$

where dp_{Ve} is the differential pressure measured at the Venturi meter available in the HPP Safien Platz. The coefficients in this formula were determined during thermodynamic efficiency measurements, carried out by Sulzer Hydro in 1995. Assuming that these coefficients are still valid, the index discharge measurement with the Venturi meter becomes even an absolute measurement.
The types and disposition of instruments used for the index tests and the additional signals from the control system are summarized in Figure 4.

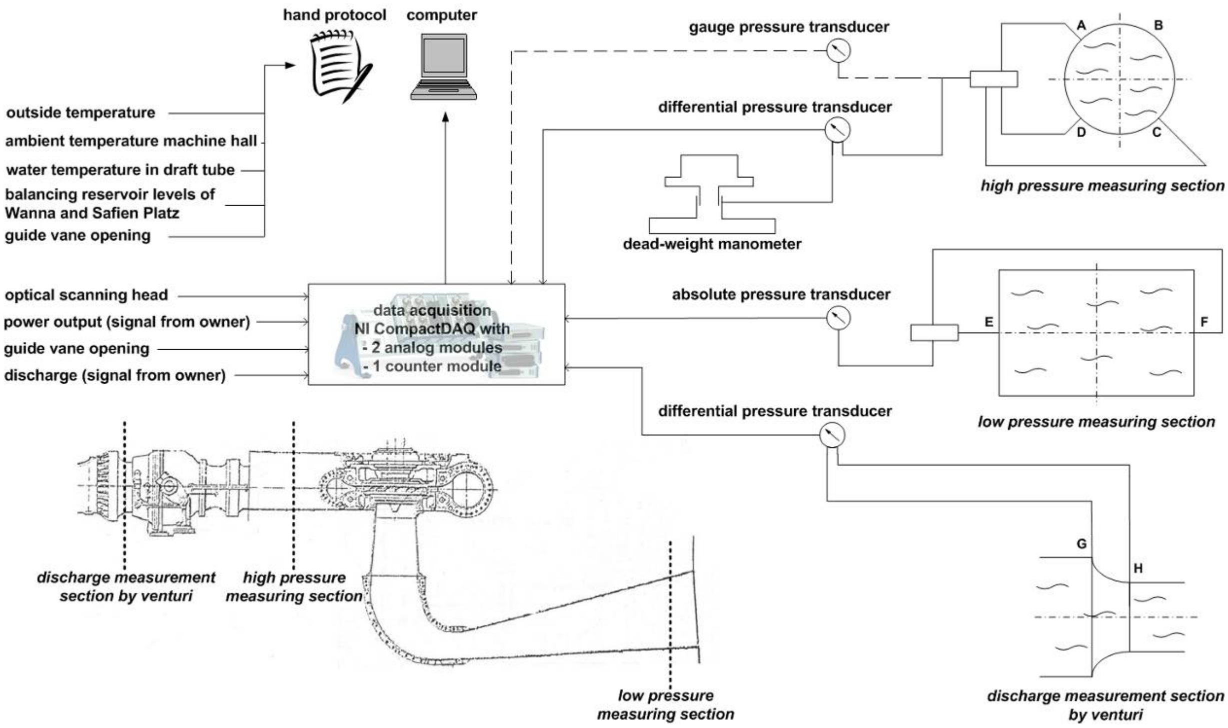

Fig. 4: Measurement arrangement and signal acquisition for index tests at HPP Safien Platz

Figure 5 shows a compilation of the results of index testing at the Safien Platz tests (Abgottspon [5]). Included are the results from the index tests in February 2007 before and February 2008 after the maintenance works. Also added are the results of the thermodynamic efficiency measurements carried out by Sulzer Hydro in 1995. The diagram shows the relative index efficiencies referenced to the best efficiency point of the thermodynamic measurements from 1995.
The difference between the index efficiencies before and after maintenance is 2.3% at 27MW (partial load) and 1.8% at 45MW (full load). We observe that the efficiency curve is shifted by about 2 to 3% to the left for the measurements after the repair works. This is an indicator for the reduction of the leakage flow with the renewed labyrinth seals. Assuming that the formula for the discharge evaluation

did not change with time, the remaining decrease of about 0.2% compared to the measurements of 1995 can be attributed to increased friction losses due to the coating of the parts which were not present during the acceptance tests of 1995.

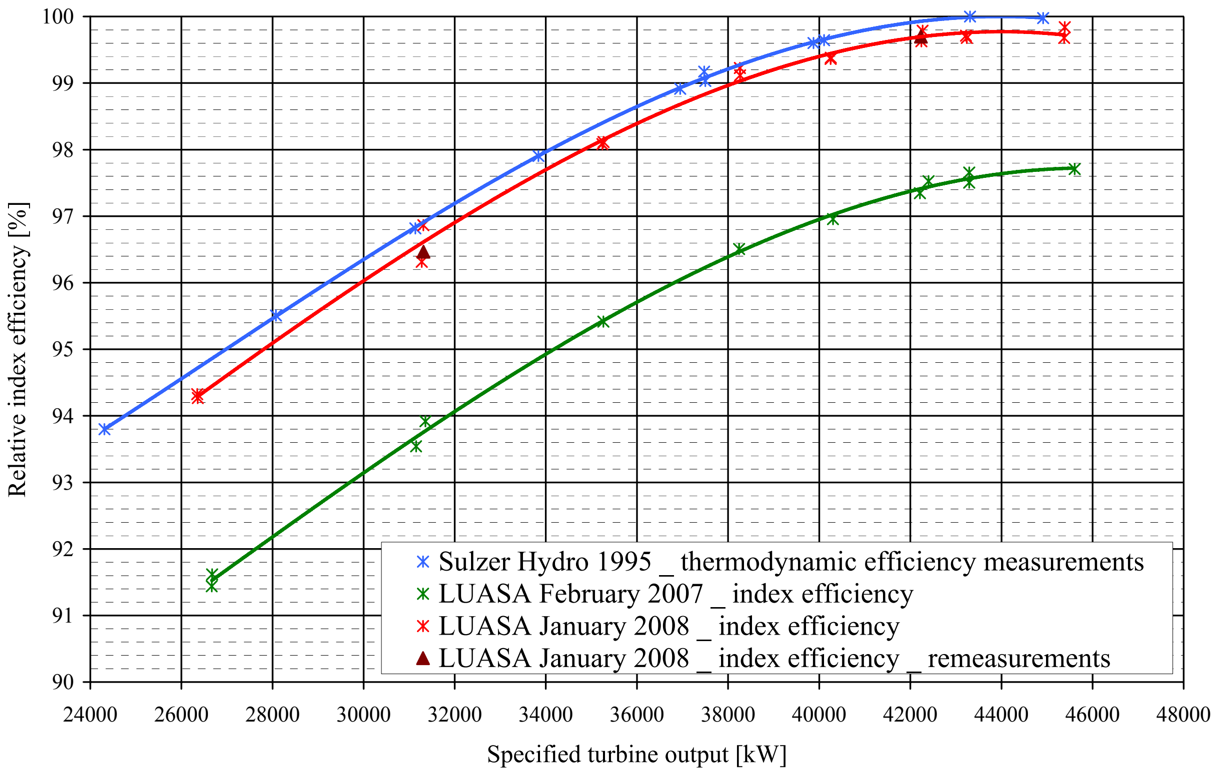

Fig. 5: Comparison of index efficiencies before and after maintenance

All measuring points were repeated twice. The repeatability of two consecutively measurements is within 0.2%, with the exception of one part load point. After each series of measurements some measuring points were repeated, brown points in Figure 5 at 31MW and 42MW. The deviation of these two points from the trend curve is less than 0.2%.

4 Sliding gate method

The sliding gate method for index testing follows the general procedure as the traditional method of index measurement described above. The difference is that during data acquisition a gate or the guide vane apparatus is slowly opened and closed according to a prescribed procedure. The success of the method depends on the fact that the unit will be in quasi-steady state operation, as described by Almquist [2], [3], [4].

The sliding gate method has two main advantages:

- the time of testing can be significantly reduced,
- the result is a continuous efficiency curve and therefore more information on efficiencies over full operating range is acquired.

Quasi-steady state conditions can be achieved with small power steps as applied during the tests in the HPP Safien Platz, which was in this plant the simplest way to adopt the procedure.

The slower the power regulation is carried out the more points at a given sampling frequency will be available for a least square fit of a trend curve of efficiencies. The sampling rate chosen for the sliding gate method was 1Hz. During the first measuring campaign in February 2007 two different ramps were tested, one with 0.5MW steps every 45 seconds and one with 1MW steps every 90 seconds, see Figure 6.

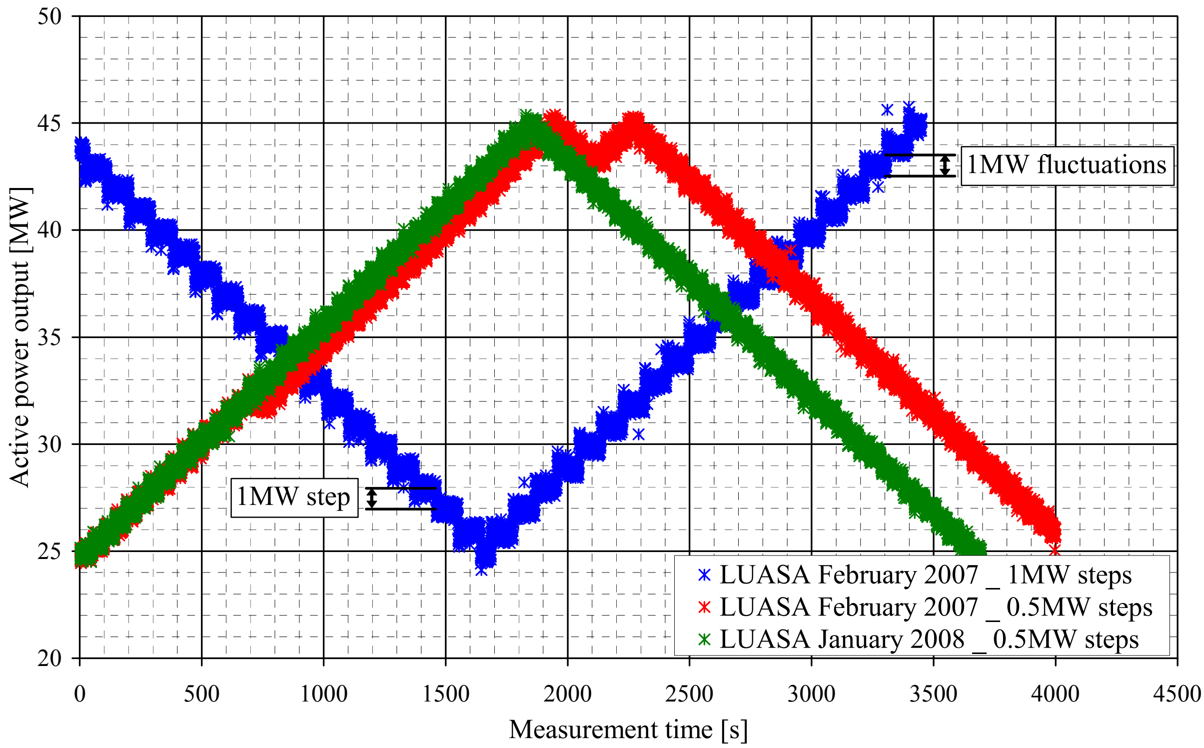

Fig. 6: Variation of active power output during sliding gate measurements

The duration of both measurements was about one hour. An analysis of the results of the measurements with these two different ramps showed identical efficiency trend curves. This is a good indicator for quasi-steady state operating conditions during the efficiency measurements for both types of ramps. Fluctuations of power in a band of about 1MW were observed on all ramps. These fluctuations seem to be inherent to the control system.

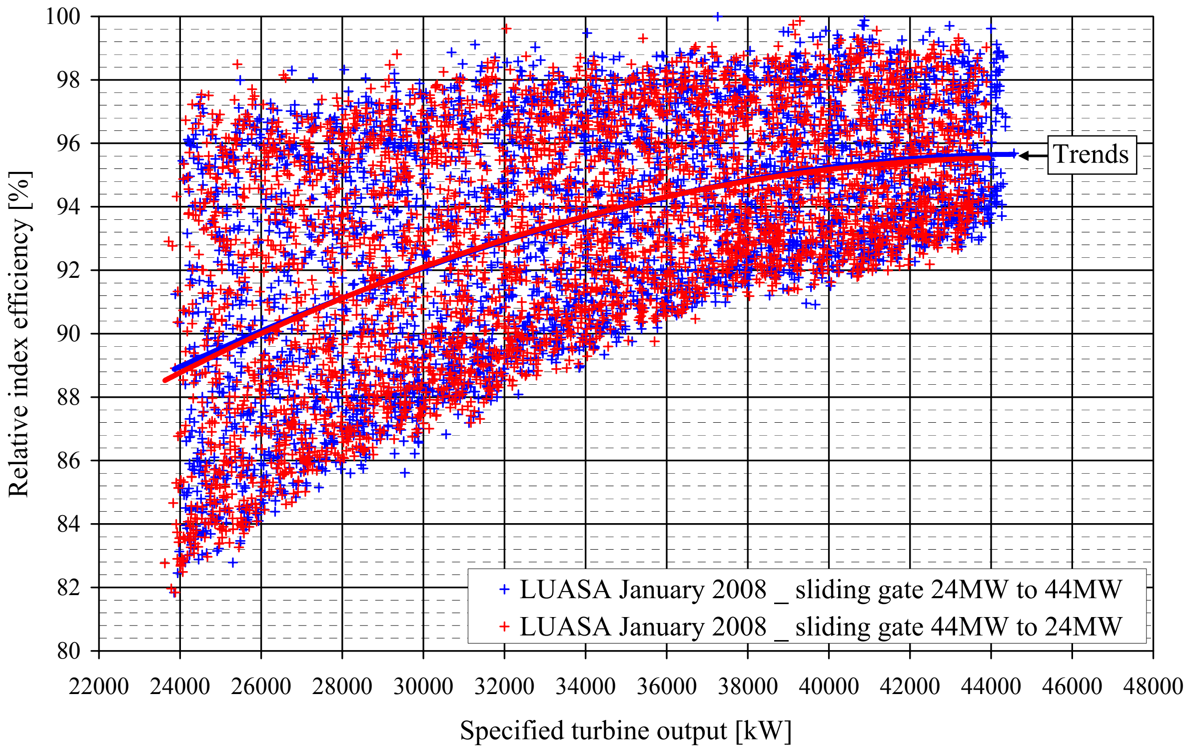

Fig. 7: Comparison of increasing (blue trend) and decreasing (red trend) index efficiencies

Figure 7 shows increasing and decreasing index efficiencies corresponding to the programmed green ramp in Figure 6 of January 2008. The efficiency is evaluated for each sampled point. The measurements and the efficiency evaluation are similar to the traditional index method (equations 1 to 4) with the exception of the active power output. For the traditional method the active power output was determined from the energy meter using an optical scanning head and by measuring the time for a given number of measuring pulses. For the sliding gate tests the active power output signal from the control system was used. The analysis of the differences of the two power measurements showed deviations of less than 0.2%.

The relative index efficiencies are referenced to the maximum point of the sliding gate efficiencies and are displayed as a function of the specified turbine output. The observed efficiency fluctuations are high and increase towards partial load. Major contributions are due to pressure fluctuations in the Venturi meter. Further effects might come from the partial load vortex formation downstream of the Francis runner, from the surge tank oscillations or from pressure wave propagation in the penstock.

Important for comparison of the increasing and decreasing efficiencies are the trend curves which are determined from a least square fit of the data. Both trend curves show to be almost identical. This allows the conclusion that the ramp durations could eventually be reduced. In any case increasing and decreasing ramps are necessary to detect possible hysteresis effects.

5 Comparison of the traditional index tests and the sliding gate method

Figure 8 shows a comparison of the instantaneous sliding gate efficiencies in the range between 40MW to 44MW with efficiencies from each sample of a steady state point at a constant guide vane opening. The fluctuations in instantaneous efficiencies lie in a band of almost ±4% around the mean. However, the trend of the sliding gate perfectly fits the efficiency point of the steady state measurement. There is a difference of less than 0.1% between the trend curve of the sliding gate measurements (blue line), the mean value of the averaged samples (red point), and the steady state point of the traditional index measurement (green point). The fluctuation of the samples of the traditional index test is of the same order as the fluctuations observed during the sliding gate measurements. This means that also the steady state data have the same level of short time fluctuations which do not have any influence on the resulting efficiency if enough data are averaged. Almquist [4] reports similar observations.

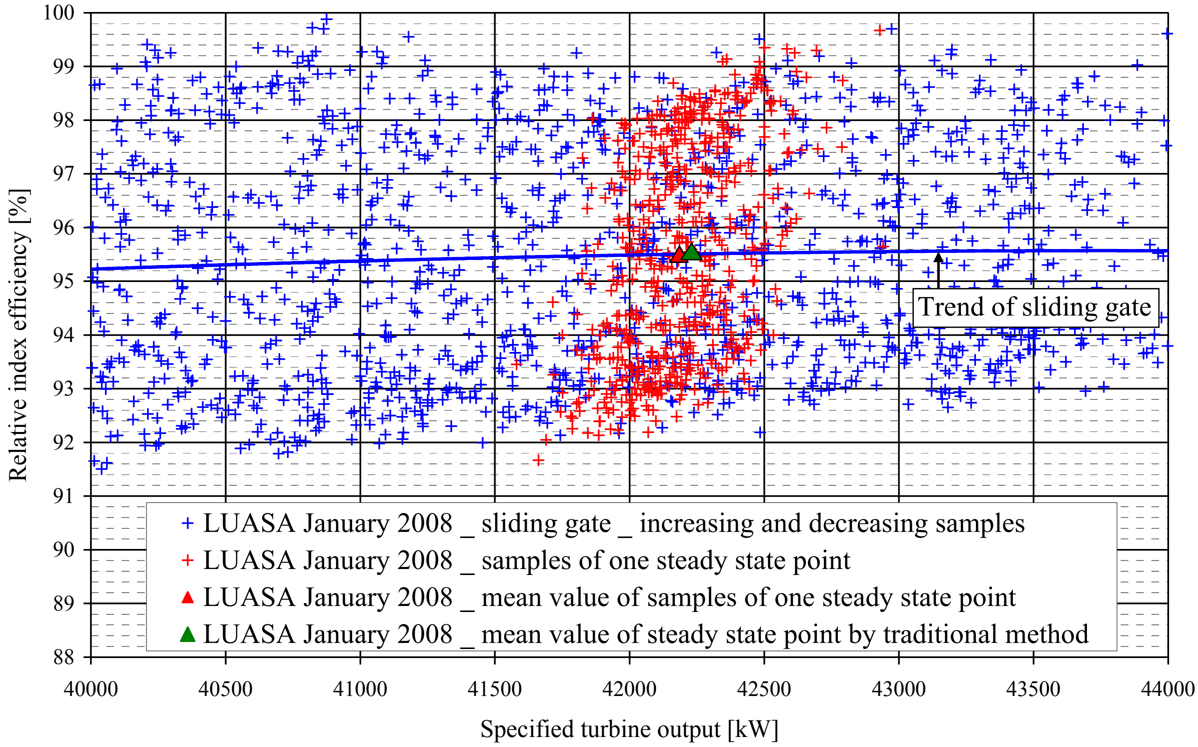

Fig. 8: Comparison of sliding gate measurements and of data for one steady state point acquisition

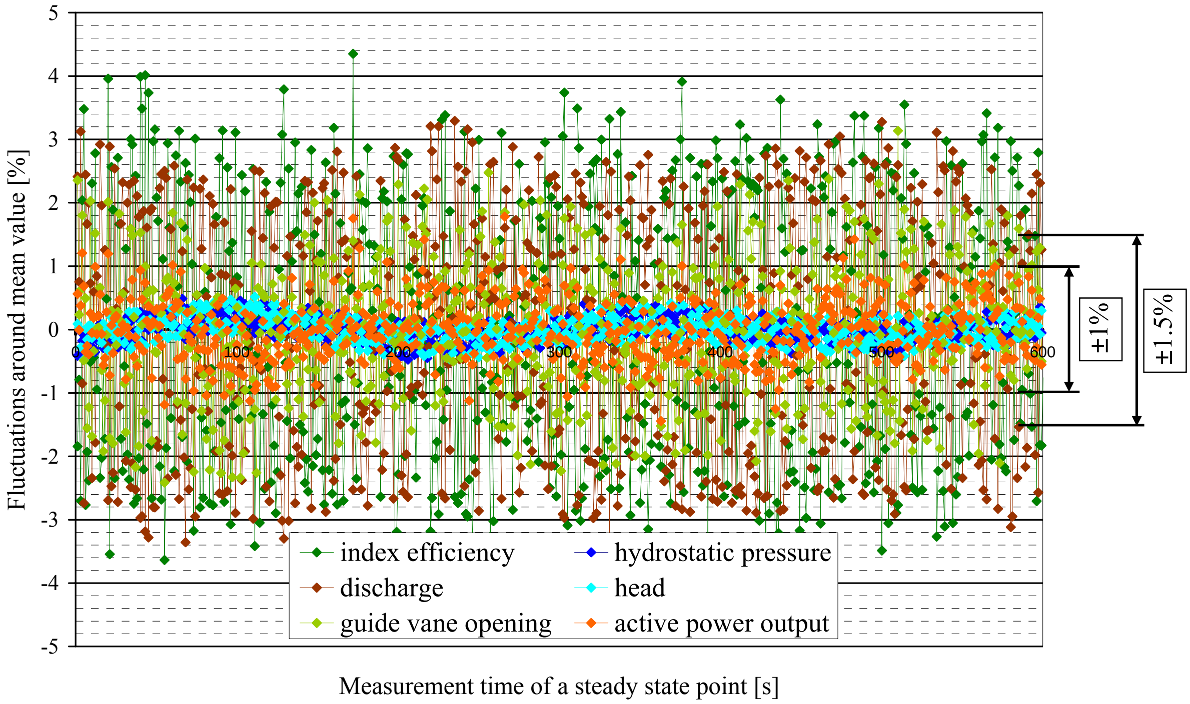

Fig. 9: Fluctuations and variations of data during acquisition of a steady state measuring point

In Figure 9 the fluctuations of the individual quantities for efficiency evaluation of a steady state point are displayed as a function of the acquisition time. The data correspond to the data of the efficiency fluctuations shown in Figure 8. It can be seen that major contribution of the fluctuations in efficiency comes from the discharge fluctuations, that are the pressure fluctuations in the Venturi meter.
The IEC standard 60041, section 5.2.1 [1] defines the expression "fluctuations" as high frequency changes (more than 1Hz) and "variations" as changes over longer periods. Here we define fluctuations also for slightly lower frequencies, because the water hammer frequency was estimated to be around 0.5Hz (with penstock length 740m).
Furthermore, IEC 60041 requires that the variations of specific hydraulic energy shall not exceed ±1% of the average value of specific hydraulic energy and variations of power shall not exceed ±1.5% of the average value of power (both limits draw into). Both quantities lie in this case within these limits. In the hydrostatic pressure and head variation we observe an underlying harmonic oscillation, which is attributed to the surge tank oscillation.
Figure 10 shows the filtered signal (calculated with Butterworth second order) of the hydrostatic pressure measurements of the data shown in Figure 9. The period of oscillation corresponds to the surge tank oscillation. If possible, we choose approximately two periods of surge tank oscillation for all our site tests. The influence of the measuring duration is especially important for the index tests, as can be seen from the examples in Figure 10, where approximately half a period of the oscillation is for averaging.
For a good average the duration of acquisition should correspond to an equal number of periods of the surge tank oscillation. E.g. if the measurement duration is chosen to be 2 minutes and the start of the acquisition is set as shown in Figure 10 the efficiency error can be ±0.13%.
Figure 11 shows the results of the Safien Platz traditional index efficiency points and the trends resulting from the sliding gate tests. Both tests before and after the repair works are displayed. The trend curves of the sliding gate measurements are averaged curves from increasing and decreasing efficiencies.
The excellent agreement of steady state index efficiencies with the sliding gate trends over full operating range is obvious. The additional information we get from the sliding gate curves is that obviously no discontinuities occur inbetween the measured points. For future sliding gate measurements longer data acquisition has to be foreseen for maximum power output. In the present measurements full load measurements were not included in the sliding gate measurements.

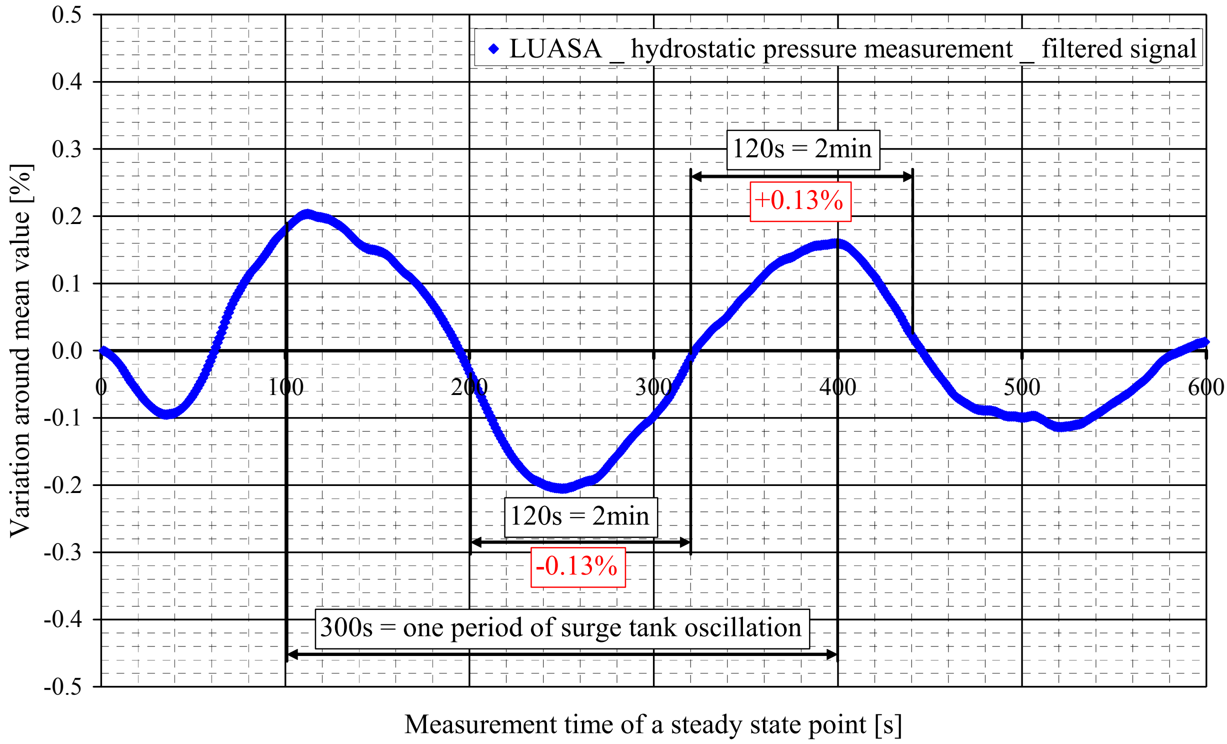

Fig. 10: Variation of filtered hydrostatic pressure measurement during acquisition of a steady state point and influence of the duration for averaging

The entire measuring duration for the traditional index test in the case of Safien Platz was about 5 hours. The time duration for the sliding gate measurements was about 1 hour. Not included in these durations are of course zero point measurements or installation times.

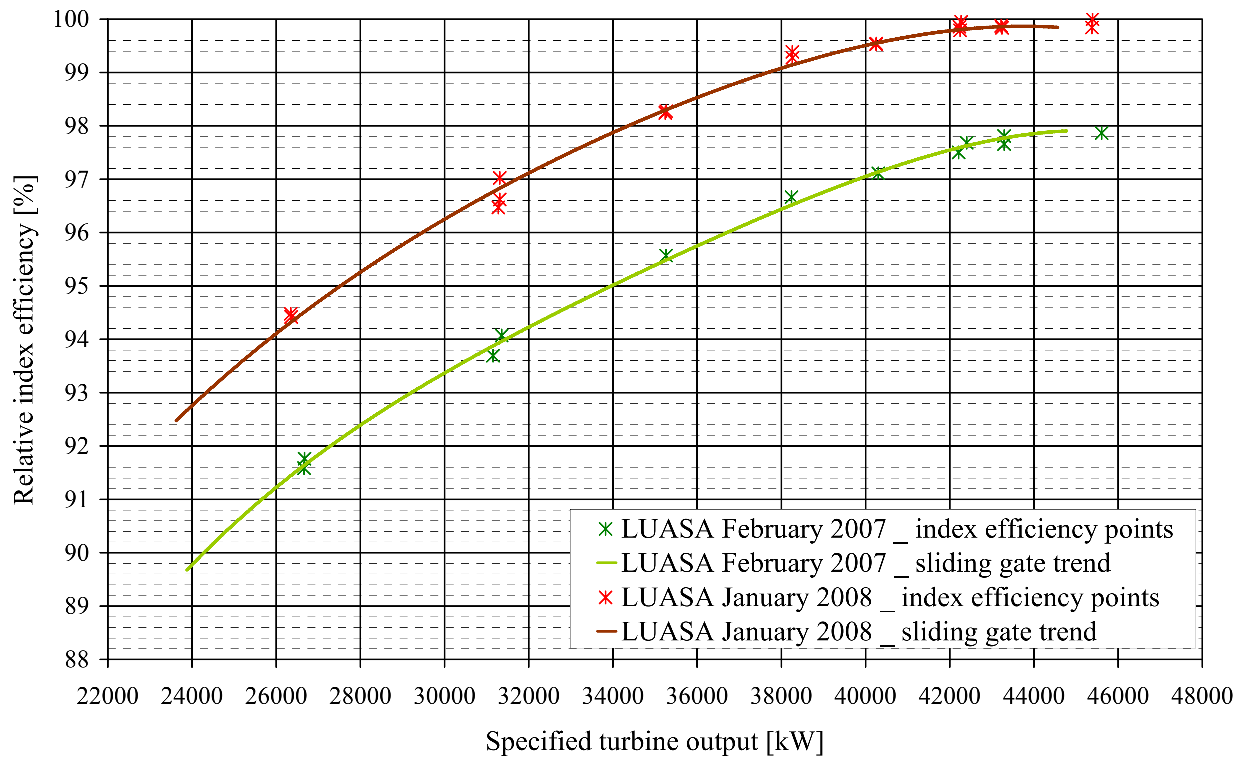

Fig. 11: Comparison of traditional index efficiency points and sliding gate trends

6 Conclusion

The Kraftwerke Zervreila AG could well quantify the benefits of their maintenance works on the efficiency level with the performed index tests. For future planning of maintenance they have now a good basis to estimate efficiency losses. Efficiency differences of 2.3% at partial load and 1.8% at full load were found. This improvement is mainly due to the reduction of the leakage flow (revision of labyrinth seal).
Additionally, new experience was gained with respect to the sliding gate method. On both tests, before and after maintenance, the results of the trends from the sliding gate method have an excellent agreement with the steady state measuring points. The sliding gate method needs quasi-steady conditions, which were realised for the HPP Safien Platz by decreasing and increasing power output with 1MW and 0.5MW steps over a period of one hour. The major advantage of the sliding gate method is a continuous efficiency curve instead of an approximation curve through discrete points. Thus, more information on efficiencies in the entire operating range can be acquired even in a considerably shorter time.

Acknowledgment

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