

# Operating experience with a generator stator end-winding vibration monitoring system

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## ABSTRACT

The economic performance of turbo generators and hydro generators can be considerably enhanced by on-line monitoring techniques. Because vibration is an important index showing the soundness of rotating electrical machines, they can be used for early detection of anomalies and troubles. Beside end-winding and shaft vibration, other parameters can be monitored and integrated for comprehensive condition assessment of the entire generator. The extent of such additional data depends on individual generator design.

Generator end-windings experience mechanical vibration during operation. The frequency of this vibration is twice the electrical synchronous frequency of the generator. High vibration can lead to loosening of entire end-winding support system, wear of insulation material, rupture of coil, and fatigue cracking of conductors, all of which require extensive out-of-service repairs.

A Fibre Optic Vibration System is used to measure the vibration of high voltage generator end-windings where conventional hardwired transducers cannot be safely mounted. Its database is helpful to anticipate generator end-winding vibration problems, predict future maintenance needs, extend intervals between inspections, and minimise maintenance downtime.

This paper presents the system to measure, display, evaluate and store stator end-winding vibration measurements for predictive maintenance in order to improve the economic performance of power plants. It describes installation procedure and operation experience of the system on four identical generators at the Beznau nuclear power plant in Switzerland.

## 1. FIBRE OPTIC VIBRATION SYSTEM

On-line monitoring system can considerably enhance the economical operation of turbo and hydro generators. Vibration and process data (e.g. temperature, partial discharge, hydrogen pressure, hydrogen purity, flow rate, shaft voltage and field winding shorted-turns etc.) can be monitored and used for evaluation of complete generator condition. This is very significant when users tend to stretch the overhaul intervals more and more: ten (10) to twelve (12) year intervals are not rare.

Hydro generator application of fibre-optic vibration system is more or less limited to generator-motors of pump storage plants because of their very demanding operating regime; several starts and mode changes (e.g. SpinGen to Generate) a day. This causes the generator-motors to undergo high thermal and mechanical stress causing quick deterioration of the bar insulation, bar solder joints, and bar wedging.

Since vibration and particularly stator end-windings are very important for the detection of premature anomalies and problems, they are vital in evaluating the generator condition. Because end-winding vibration depends on generator operating conditions, a reliable monitoring system was designed to integrate additional process parameters (Fig. 1). It allows trending and statistic reports regarding the end-winding vibration behaviour. This provides comprehensive data presentation correlated with machine operating conditions without the long and difficult interpretation of printed data.



*Fig. 1: Fibre Optic Measuring System*

Stator end-windings are excited by electromagnetic forces during the operation. The vibration amplitudes are proportional to the square of the current and the frequency is twice the electrical line frequency. On end-windings with loose supports, larger vibration amplitudes can be measured at partial load than at full load. Higher end-winding vibration quickly leads to loosening of the end-winding basket, insulation abrasion or cracks, as well as fatigue rupture of bars and solder links. All these failures entail long shutdowns and considerable costs. Consequently, a monitoring system not only provides valuable data to plan revision and maintenance measures, but also helps reduce downtime in case of failure shutdowns.

A typical fibre optic accelerometer is shown in Fig. 2. Its unibody design consist of a small size sensor head of non-conducting material, a fibre optic cable, and a feedthrough connector with built-in optoelectronic circuitry. It is sensitive to vibration in a single axis. The sensor head is located at the end of a two-strand, multimode, optical fibreglass cable. One fibre carries the light generated by the conditioning electronics for illumination; the sensor head returns an optical signal of variable intensity through the second fibre. The electrical isolation of the optical circuit allows the sensor to be mounted directly to the stator coil ends.



*Fig. 2: Fibre Optic Accelerometer with feedthrough conditioner*

In the conditioning electronics, the optical signal is converted to an electrical signal by optoelectronic circuitry, processed and amplified to an acceptable level. The resultant measured signal is a calibrated analogue signal of 100 mV/g proportional to vibration acceleration which can be further processed by a computer. A specially designed software provides signal processing, display and data storage. In addition, vibration velocity and displacement are processed. After Fast Fourier Transform (FFT), the measured signals are displayed as amplitude-frequency spectrum (Fig. 3). The system can be used in stand-alone operation or linked to plant control system.

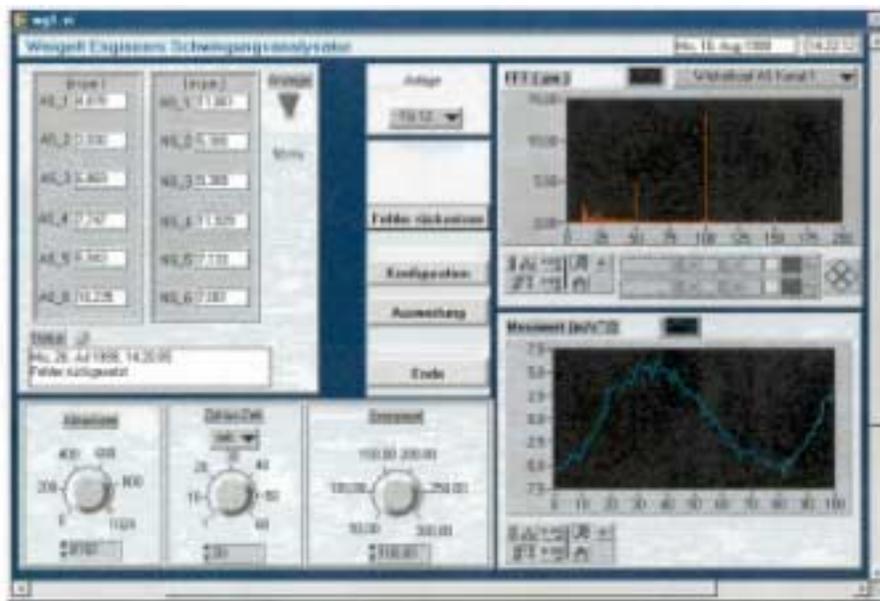


Fig. 3: Overview of software user interface

## 1. INSTALLATION OF FIBRE OPTIC ACCELEROMETERS

The fibre optic system as shown in Fig. 1 consists of fibre optic accelerometers and cables, power supply and a computer. Such a system can be installed on generators in about seven days during an overhaul. Usually, twelve (12) accelerometers are installed per turbo-generator, six (6) sensors on each side. Sensors are required for each group of phases in radial and/or tangential directions. On pump generating sets, large generators, and depending on winding design six (6) to twelve (12) or more accelerometers may be necessary. Current experiences on hydro generator propose radial measurement points at the exit of the bar from the laminations and tangential measurement points at the bar solder links.

The fibre optic accelerometers are used for vibration measurements where conventional accelerometers are precluded. As previously mentioned, the accelerometer is sensitive in only one direction. Consequently, it is possible to monitor vibration of an installation in radial, axial and tangential directions. Fig. 4 shows how accelerometers and cables are installed on the end-windings. It is important to respect the minimum bending radius of the optical cable to avoid breaking. It is also important to mention that the feedthrough units must be equipped with O-rings withstanding the hydrogen environment of the generator and must be mounted on a flange (Fig. 5). The electrical signals are available at the feedthrough conditioning unit.



Fig. 4: Installed fibre optic accelerometer for radial measurement



Fig. 5: Sealed flange with six feedthrough conditioners and cable

## 2. IMPLEMENTATION AT BEZNAU NUCLEAR POWER PLANT

The Beznau Nuclear Power Plant (KKB) in Switzerland is owned and operated by Nordostschweizerischen Kraftwerke (NOK). It is located at the confluence of Aar and Rhine Rivers, on an island created by the hydro power station water channel and the Aar River (Fig. 6). The turbosets were commissioned between 1969 and 1971.



*Fig. 6: Overview of Beznau Power Plant*

The KKB nuclear power plant consists of two identical blocks equipped with Pressurised Water Reactors. The secondary circuit of each reactor is connected to two turbosets. The KKB plant produces base load power for the grid and generates a nominal net power of 365 MW per reactor.

A total of four two-pole generators, each rated at 228 MVA with stator voltage of 15.5 kV, are installed. The rotor and stator windings are hydrogen cooled (Fig. 7). Each turboset has accumulated more than 200'000 operating hours. Normally, inspections are done in the summer when power demand is ensured by NOK hydro power plants.



*Fig. 7: Hydrogen-cooled two pole generator (228 MVA and 15,5 KV stator voltage)*

Insulation abrasion of the stator end-windings was always observed (Fig. 8) on past overhaul and maintenance shutdowns of the turbosets TG11, TG12, TG21 and TG22. In view of planning future overhauls and reliable power plant operations for the next 20 to 30 years, NOK decided to monitor the effective end-winding vibration and take corrective actions from this baseline.

A fibre optic accelerometer system was installed to measure and evaluate end-winding vibration.



*Fig. 8: Insulation abrasion between end-winding support elements*

### **3. PLANNING FUTURE GENERATOR OVERHAULS**

Until now, each block was refuelled every year along with refurbishment of all main components that cannot be maintained during operating hours. At the occasion, one generator of each block was serviced; one would have a large overhaul with rotor disassembly while the other would only be heavily tested for diagnostic with the rotor installed. This meant that a complete overhaul of each generator with rotor disassembly was done every four years.

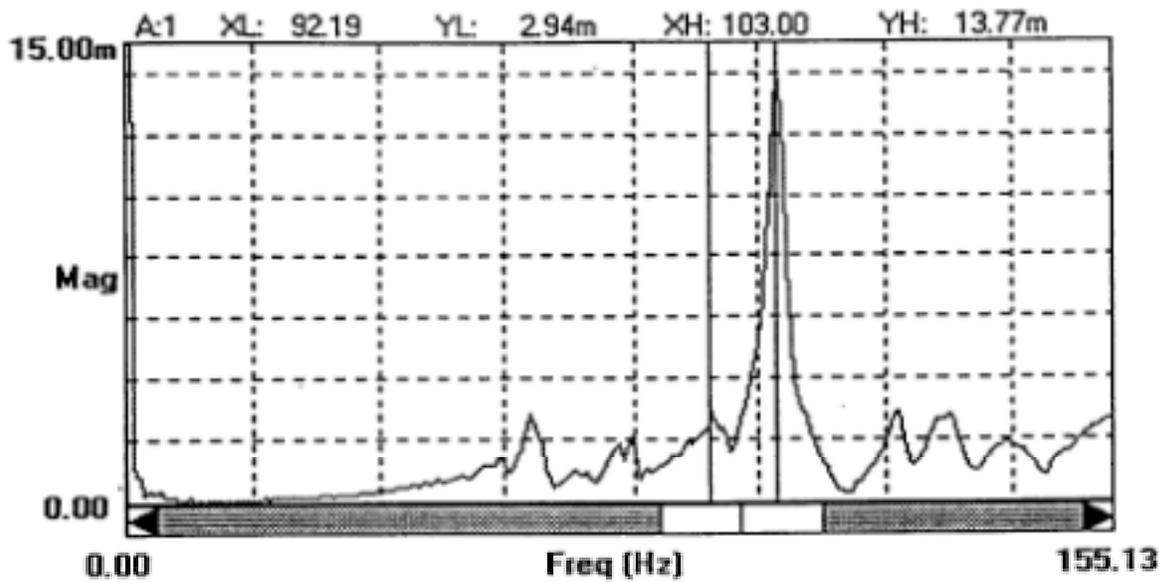
These heavy tests and maintenance works were also necessary to check the old rotor retaining ring material, perform end-winding maintenance because of the insulation abrasion, check stator bar wedging system and fix loose wedges, as well as other maintenance works to the turbines. Aside from insulation abrasion of the end-windings, the introduction of necessary improvements has allowed the extension of overhaul intervals of the generators from four to eight years representing a reduction of approximately 30 to 40% of total revision costs.

However, the necessary generator condition checks still remain and, in order to detect possible premature changes, an on-line monitoring system was installed. Coupling capacitors were installed on the generator main switch in order to allow partial discharge measurements of the stator coils and complete transformer derivations at any time.

Following recommendations of the manufacturer, special generator diagnostics shall be performed before and during the overhaul shutdowns. The already installed fibre optic measuring system complements the on-line monitoring system of the four generators.

### **4. MEASURES FOR ADDITIONAL 20 TO 30 YEARS OF OPERATION**

It shall be understood that the measures described herein are limited to the four generators. In order to determine the reasons for the end-winding insulation abrasion, the manufacturer conducted dynamic structural tests in 1992 and 1994. The results showed that the resonance frequency of the four node mode was slightly above 100 Hz with a high dynamic compliance in the tangential direction (Fig. 9)



*Fig. 9: End-winding resonance at 103 Hz at the driven-end*

The vibration analysis of each generator was done at the time of an overhaul shutdown at room temperature. At the non-driven end, the end-winding stiffness was higher compared to the driven end because of the lead bars and the parallel rings.

As end-winding temperature increases under continuous operation, a reduction of resonance frequency by a few Hertz is expected. In such case, the reduced resonance frequency of the four node mode could match the 100 Hz excitation force and amplify the vibration. With the high compliance of the end-windings in the tangential direction, high vibration amplitudes are expected, as the observed insulation abrasion had already well confirmed.

Two possible measures were discussed: rewinding the stator or modifying the end-winding supports. Rewinding the stator implies a longer loss of energy production and higher investment costs which were mandatory to avoid. Instead, it was preferred to defer the rewinding for the remaining lifetime of the generators and take all actions in order to prevent loss of production due to failures.

Considering the future overhaul plans of both blocks and reliable operation for an additional 20 to 30 years, it was decided first to measure the end-winding vibration under operating conditions. In order to do this, a fibre optic measuring system was required. Based on the measurement results, adequate maintenance actions would be decided.

After these measurements and also several electrical tests made on one generator showed a good condition of the stator winding, a modification of the end-winding fixation was studied. By means of a tangential wedging and relative low expenditures, a reduction to acceptable values of the end-winding dynamic flexibility in tangential direction appeared possible as well as a shift of the four node mode resonance frequency. The tangential wedging of each end-winding would be linked to a rigid arch (Fig. 10).



*Fig. 10: Example of tangential wedging of end-winding*

After in-depth evaluation, NOK decided to proceed with the tangential wedging of one generator. As soon as results will be available, a decision will be taken for the other three generators.

## **5. VIBRATION MEASUREMENTS BEFORE END-WINDING MODIFICATION**

Fibre optic accelerometers with respective feedthrough conditioning units were first fitted to end-windings on generator TG11 and TG12 and later on generators TG21 and TG22. Since it was intended to wedge the end-windings in tangential axis, six accelerometers on each side of the generators were installed to measure radial vibration (Fig. 4). The accelerometers are located on stator bars with the longest non-supported axial length. In addition, at the driven end, an accelerometer was mounted at a phase separation to measure the tangential vibration (Fig. 11).



Fig. 11: Installed fibre optic accelerometer for tangential measurement

The measured vibration depend on current apparent power and on cooling gas temperature; therefore small changes of cooling gas temperature influence the vibration amplitudes. This depends on the fact that the operating resonance of the end-windings is more or less identical to the electrodynamic excitation force of 100 Hz. Figure 12 and 13 show the vibration behaviour of the end-windings during power changes and during cooler cleaning.

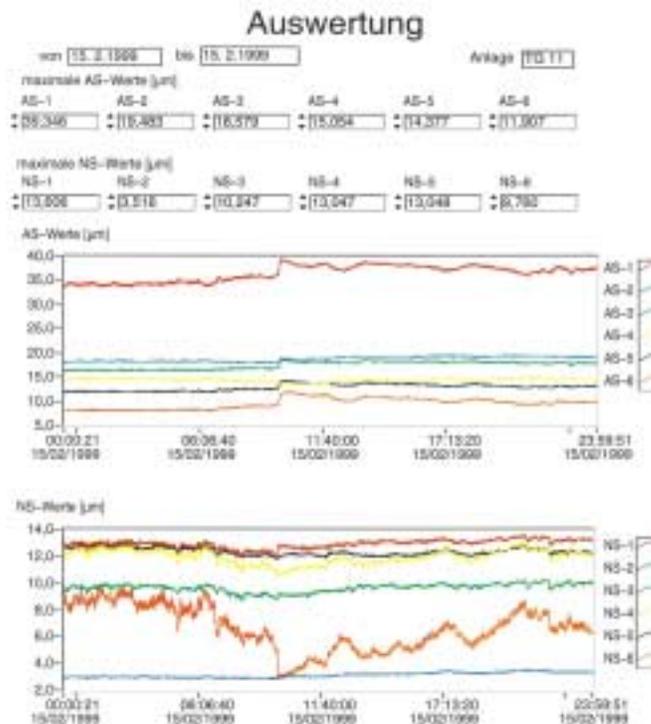


Fig. 12: Vibration behaviour of the end-windings during power changes

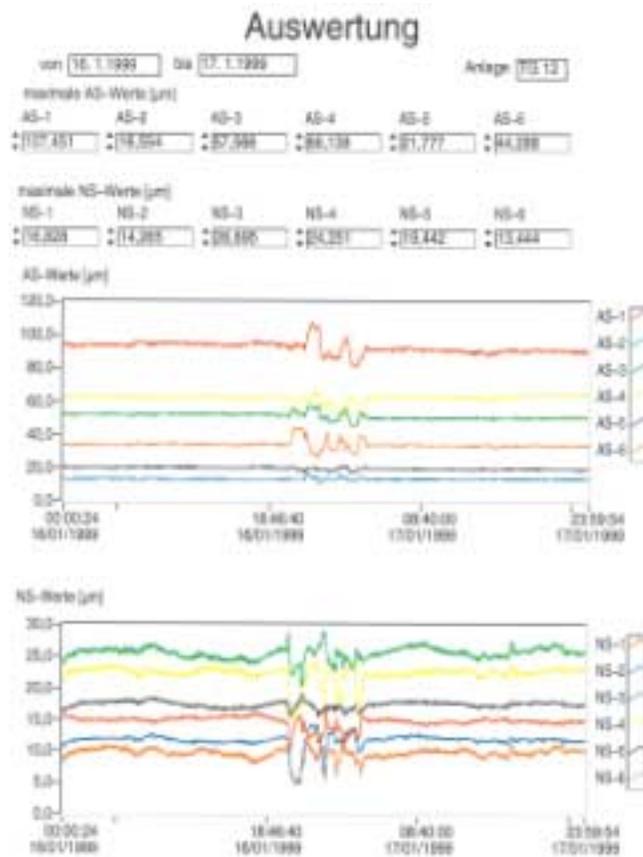


Fig. 13: Vibration behaviour of the end-windings during cooler cleaning

Because of the identical design of the four generators, it was expected to obtain a similar vibration behaviour. However, the evaluation of the measured end-winding vibration provides the following results:

- 100 Hz vibration amplitude in tangential direction at the driven end during start up over several hours:
- 100 Hz vibration amplitude in tangential direction at the driven end at full load:

TG11	136 mm
TG12	212 mm
TG21	110 mm
TG22	189mm

TG11	38 mm
TG12	97 mm
TG21	70 mm
TG22	101 mm

The above results show that the vibration behaviour of identically designed generators can be very different. All radial vibration readings at the driven and non driven ends remained below 70 mm. Depending on the end-winding supports, only experience-based vibration limits can be given; they will be based on stator end-winding looseness, insulation abrasion and cracks. For the KKB generators, a vibration limit of 70 mm has been imposed because insulation abrasion was observed over years.

More attention shall be given to the vibration during start up especially because they last for hours or days and lead to ruptures of end-winding links. The high vibration during start up is based on cold core laminations and decrease as temperature rise. Multiple start-ups may be sufficient to loosen the entire end-winding basket.

Without corrective actions, accelerated insulation wear is expected over the next years. Existing oil in the generators accelerates the process. In the case of high vibration, voids appear between the end-winding components and fill up with oil over time. Oil combines with insulation wear powder to form a grinding paste capable of totally loosening an end-winding basket within days or weeks. As experience showed, vibration amplitudes may increase over a short period by factor 5 to 10. Such rapid deterioration of end-windings is normally beyond repairs and inevitably entails stator winding replacement.

All in all, there are plausible reasons recommending tangential wedging of end-windings. At first, this was done on generators TG12 and TG22 because of high 100 Hz vibration during start up and normal operation. Later the same corrections were done on generators TG11 and TG21. With these corrective actions, it is targeted to reliably operate the stator winding over several decades.

## **7. VIBRATION MEASUREMENTS AFTER END-WINDING MODIFICATION**

Immediately after tangential wedging was implemented on generator TG12, a new measurement campaign was carried out and a reduction of the end-winding vibration was expected.

In fact, during start up the tangential vibration went down to 118 mm (Fig. 14 and Fig. 15) instead of 212 mm before the modifications, and to 75 mm in normal operation instead of 100 mm. The maximal value of radial vibration decreased from 30 mm to 20 mm. Despite a little increase of the radial vibration for some low level channels, the reduction was in average approximately 30%.

# Auswertung

von 30.10.1997 bis 4.11.1997

Anlage TG 12

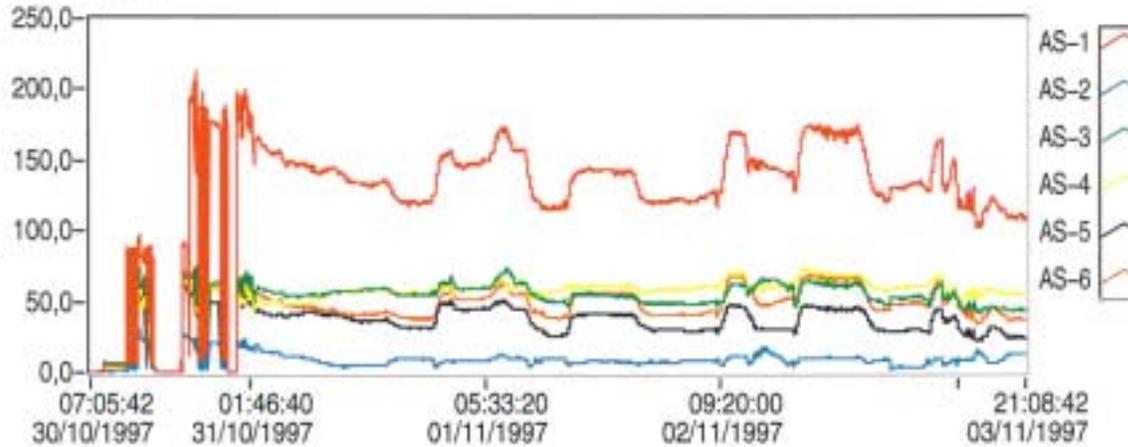
maximale AS-Werte [ $\mu\text{m}$ ]

AS-1	AS-2	AS-3	AS-4	AS-5	AS-6
212,584	29,497	74,841	72,973	70,549	75,619

maximale NS-Werte [ $\mu\text{m}$ ]

NS-1	NS-2	NS-3	NS-4	NS-5	NS-6
25,037	26,131	48,210	39,997	35,202	25,359

AS-Werte [ $\mu\text{m}$ ]



NS-Werte [ $\mu\text{m}$ ]

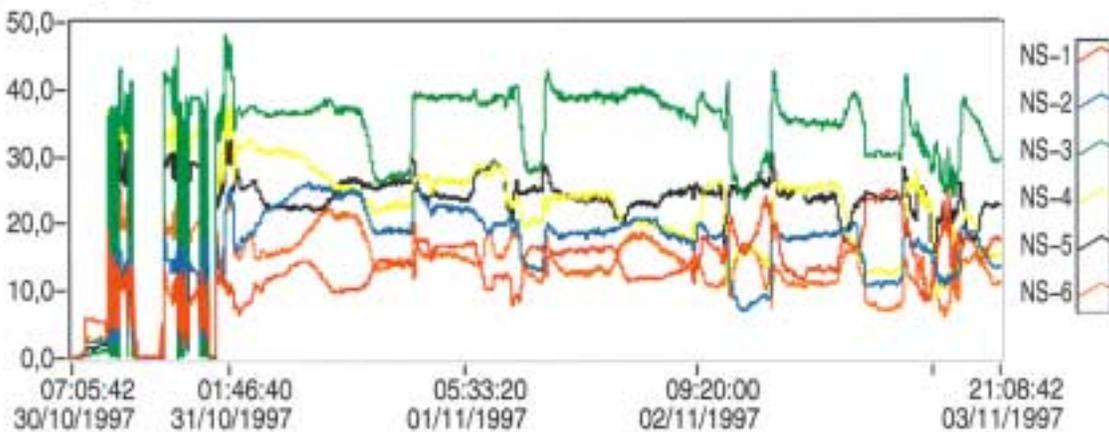


Fig. 14: Vibration behaviour of end-windings during startup before modifications

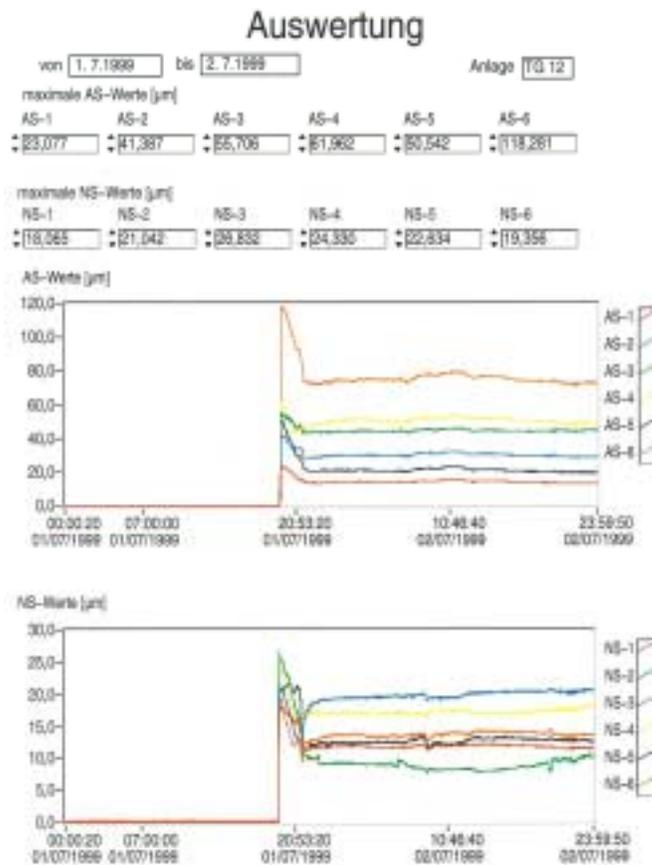


Fig. 15: Vibration behaviour of end-windings during start-up after modifications

## 8. CONCLUSION

The generators of KKB are approximately 30 years-old machines which, with targeted retrofit measures, should be reliably operated for another 20 to 30 years. To attain this high goal, searching for ways was done to survey and evaluate the existing weaknesses of important components.

Special consideration was attributed to the end-winding vibration monitoring because it represents an important and reliable measure for the condition evaluation of the generators. Weaknesses and anomalies may be prevented as well as damages avoided by goal orientated surveillance system. Generation of failures can be detected and evaluated; immediate reactions to changes taken.

Moreover, the vibration surveillance of end-windings delivers important information for planning of revisions and corrective measures. It forms a baseline for a fault free stretching of revision intervals and contributes to cost savings. With this, increasing of availability and extension of lifetime of the generators can be achieved.

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