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Ageing Generator Rotor: Refurbishment or removal from service?

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Introduction

E.ON's Datteln hard coal-fired power station, located in western Germany near Dortmund, went into operation between 1964 and 1969. The three units with a total output of 303 MW supply up to 20 per cent of the entire single phase 16.7 Hz electricity required by the German railway operator Deutsche Bahn AG to run its trains. It also supplies district heating that covers almost 50 per cent of the local heat requirements of the town of Datteln. In 2011, Datteln unit 1-3 will be replaced by a new, highly efficient hard coal-fired power plant, Datteln 4.

After so many years of use, and with the vibrations increasing, the shaft train of unit 3 of the 16.7 Hz E.ON Datteln railway power station could only be operated under severe limitations. Onsite inspections focused on the 110-ton rotor of the 138 MVA single-phase generator, where the running characteristics exhibited strong load dependencies. The vibrations were highest at rated load, and only at smaller loads were they within an acceptable range. Additionally, increasing reactive loads raised the vibration amplitude, while small reactive loads lowered it.

Operational tests

After taking several vibration measurements at different load conditions, it became clear that the rotor damper system was damaged. The plant management decided to perform a no-load saturation test (A) and a sustained short-circuit test (B) to confirm whether a faulty damper system was causing the vibration problem. While test A primarily stresses the field winding often responsible for thermal rotor unbalances, test B creates significant negative sequence currents loading the damper system of the single-phase railway generator.

In single-phase generators, the armature reaction magneto motive force (MMF) is a wave pulsating in time and stationary in space. If undamped, this wave will produce large losses in the field winding, and it is necessary to build a massive damper winding on the rotor to suppress this field. Thick damper bars sitting between rotor winding and wedges are short circuited by heavy damper baskets similar in size to a retaining ring.

Figure 1 shows the shaft displacement amplitudes of the generating set during test A. A field current of approximately 450 A produced a voltage of 10 kV (rated voltage 10,75 kV) for about 15 minutes in the no-load saturation test. During this period the change in vibration level was marginal indicating that a thermal unbalance created by the field current was not likely to be the root cause of the problem.

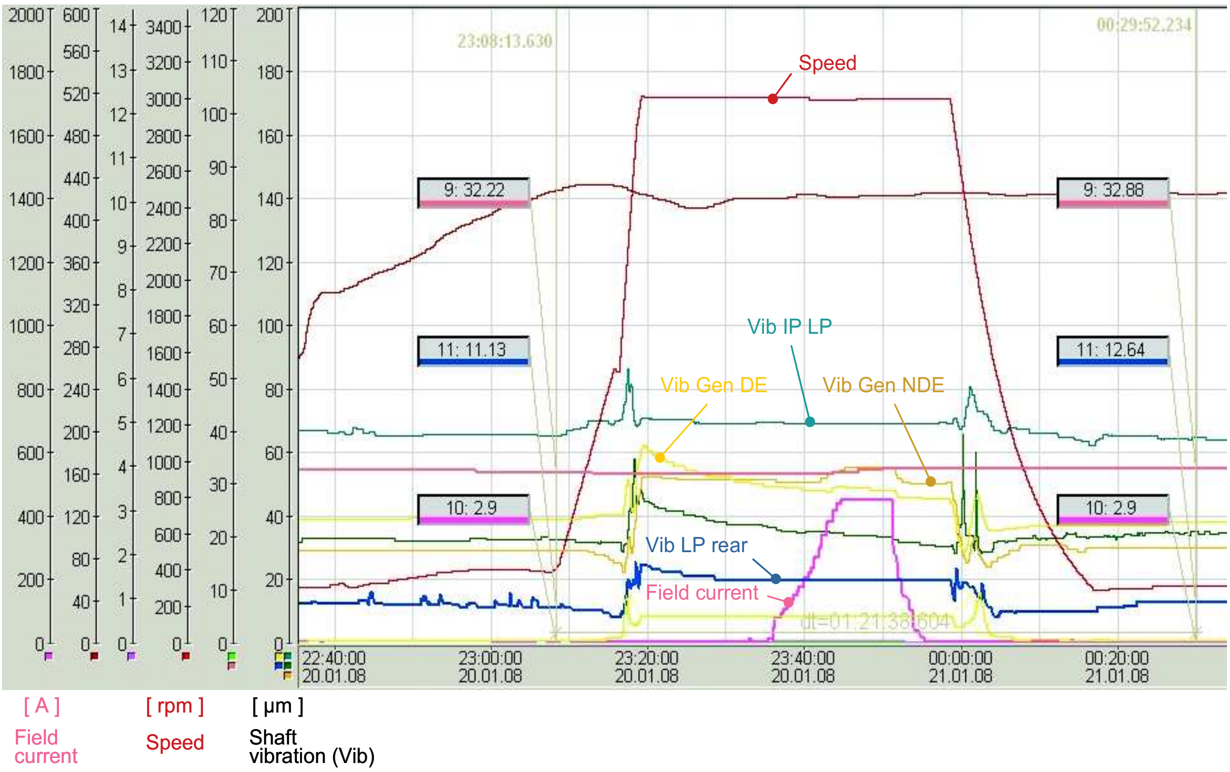

Figure 1: No-load saturation test, field current was raised to 450 A producing a generator voltage of 10 kV (voltage line not shown in this graph).

Figure 2 displays the vibration response during test B. A stator current of about 6.000 A (50% of rated value) produced a strong increase in vibration amplitudes. When the current was further raised to 8.400 A (65% of rated value) the rate of increase of vibration level was even steeper. Finally, the test was stopped when the shaft displacement at the generator non-driven end (NDE) had reached a maximum amplitude of 180 µm. Apparently, at 50% load the damper winding was no longer capable of carrying the damper current without detrimentally affecting the rotor performance. Also, the higher the damper current the stronger was the impact on the rotor unbalance.

The test results clearly identified the damper system as a probable root cause of the vibration problems, while the field current had less impact on the vibration level.

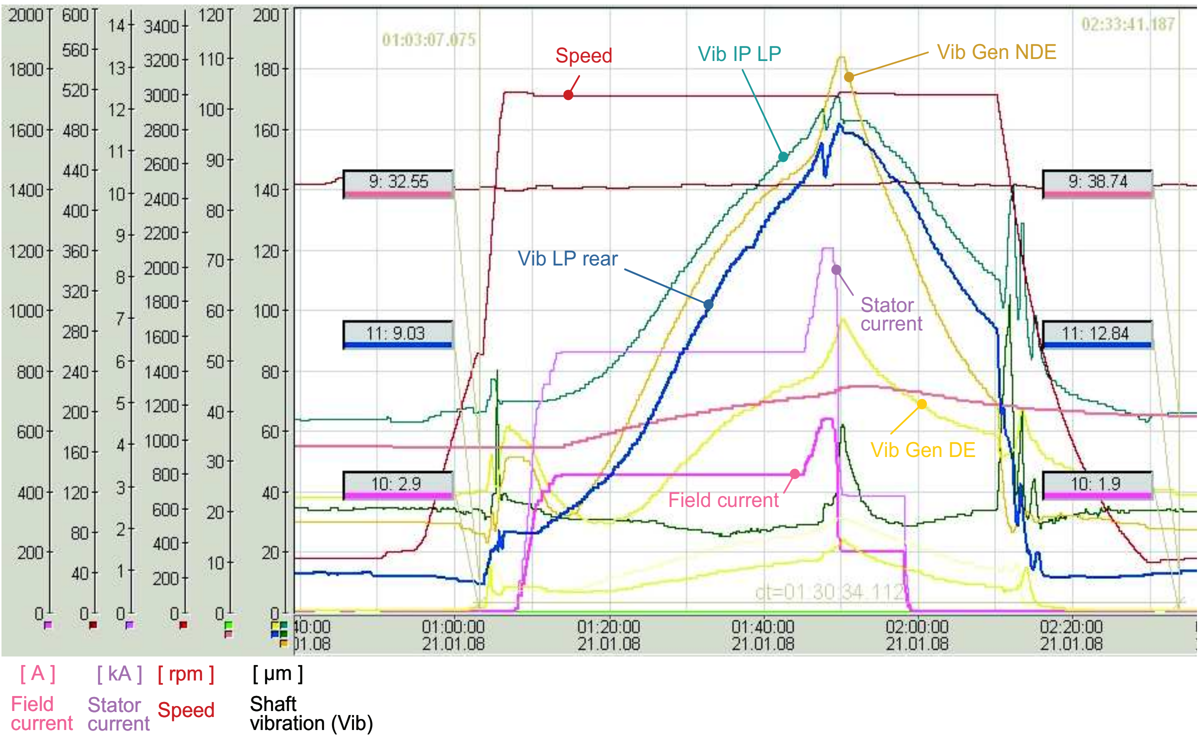

Figure 2: Sustained short-circuit test, maximum stator current reached 65% of rated current.

Rotor inspection

The generator of unit 3 was not only of major importance to the Datteln power station, but was also meant to serve as strategic spare part for another railway power station after replacement of Datteln 1-3 in 2011. Therefore, the plant owner, E.ON, looked for a supplier (partner) with expertise in large generator repairs that could quickly address the problem. E.ON eventually awarded the contract for all the required rotor inspection and repair work to Sensoplan, located in Hohentengen, Germany.

Sensoplan already had direct experience of inspecting and repairing the damper system of an almost identical unit, which provided its engineers and repair shop with first-hand data and important general information.

Figure 3: 110-ton rotor of 138 MVA single-phase generator

After the 110-ton rotor (Figure 3) arrived at the rotor service shop, electrical, mechanical and visual inspections were performed. The electrical tests indicated two interturn faults, but the insulation resistance was still in good condition, as was the mechanical run-out of the shaft at the bearing and coupling locations.

The first visual inspection revealed traces of molten copper from wedge ends and black debris in the gap between the retaining ring and rotor body, indicating that hot-spot temperatures of around 1100 °C (the melting point of copper is 1084 °C) had been occurring in the shrink seat area. As a consequence, the shrink seat insulation between the rotor body and retaining ring had burned up, producing the visible black debris described above. In single-phase generator rotors, the shrink seat is insulated to avoid high damper current entering the retaining ring.

After the removal of the retaining rings and the damper basket insulation, significant damage was found on the driven end retaining ring, the wedges and the damper basket (Figure 4). The front end of the retaining ring facing the rotor body in the pole area also showed localized melting over a length of about 200 mm. At some locations visual inspection revealed cracks in the molten zones – probably caused by large thermal stresses. The retaining rings were made from X55 MnCr 18 K, commonly referred to as 'old ring material', which is prone to stress corrosion cracking in humid atmospheres.

Figure 4: View of NDE rotor shrink seat area after removal of retaining ring

As with the retaining ring, the damage on the wedges and damper basket was mainly in the pole zone of the rotor. The wedge ends showed extended cracking and melting. Consequential damage to the rotor teeth could not be excluded at this point. After moving one wedge towards the rotor NDE, it became apparent that the primary cause of the melting was related to cracking of the damper basket fingers. A total of 14 fingers on DE were completely broken off (Figure 5), and one finger on NDE was cracked.

The fingers connect the damper bars in the rotor slots to the damper basket and are an integral part of the basket (Figure 6). When a finger breaks, the damper current flow is interrupted, forcing the current to bypass the fracture by continuing its path through the copper wedge and contacting the basket at the wedge end.

Figure 5: Damper basket NDE, 14 damper fingers were broken off

This represents an undefined electrical contact, leading to localized arcing and, consequently, the melting of the wedge ends. This arcing process was also responsible for the damage observed on the retaining ring. Such arcs carry high current densities capable of melting most materials. When driven by a stable and steady power source, their destructive power is enormous.

The disassembly of the massive damper baskets allowed the end winding to be visually inspected. This showed that the coils and turns were in good condition. Apparently, the overheating at the outer diameter of the damper basket did not reach the field winding underneath, except at one location near the slot exit of the first coil. Over a length of some 100 mm, the upper end of the slot liner showed discolouration from excessive heat, which also caused localized melting of the neighbouring rotor tooth, radially outward, in extension of the slot liner. The copper conductor itself showed no signs of overheating. There was also melting damage on two rotor teeth in the pole zone. The locations were at the slot exit just below the shrink seat of the retaining ring. The damaged area partially affected the shrink seat surface and, to a lesser extent, the wedge area at the exit of the wedge.

Repair solution

The initial assumption that the damper system was damaged was confirmed by the rotor inspection. The hot-spots in the pole zone had caused thermal stresses, which, in turn, had produced a bending moment, forcing the rotor to bow. This thermally induced bow led to an imbalance in the generator rotor that was highly dependent on the damper current and, thus, the stator current. High stator currents in single-phase machines cause large damper currents that supply more power to the arcs at the fracture of the damper fingers. This resulted in higher hot-spot temperatures, which created a larger imbalance and raised the vibration level. This is precisely the behaviour that was observed during operation of the Datteln unit 3.

Concluding that the damper system was damaged and being conscious of time needed for copper materials to be delivered, the customer proactively placed an order with Sensoplan for a new damper system, including new wedges. Through its supplier network, Sensoplan was able to arrange quick delivery for the damper system, which consisted of drawn copper bars and forged copper rings. This allowed the cracked damper baskets and molten end wedges in the pole zone to be replaced. However, the discovery of the partial melting and cracking of the retaining ring and rotor forging, as well as overheating of the slot liner indicated a new situation.

For the Sensoplan engineers, this raised the challenging question of whether a repair was possible that would allow the rotor back into service without limitations and in an economically viable time. This task was made even more challenging by the fact that the damage was located in the most highly loaded area of the generator rotor: the retaining ring shrink seat. A quick answer to the question was needed.

The first task for Sensoplan engineers was to determine the amount of 'bad material' in the retaining ring and rotor forging. After carefully cleaning the damaged area, material specialists performed non-destructive tests, took surface replicas for microstructural analysis and measured the hardness in the immediate vicinity of the damaged areas. Fortunately, things didn't turn out as badly as they could have done. The damage was localized and the rotor and retaining ring steel kept their original strength within millimetres of the melting spots.

Next, casts from the melted zones on the rotor forging and retaining ring were produced using special plastics with zero shrinkage during curing. The casts were scanned to capture the precise geometry of the missing material on the rotor. Using a geometric computer model of the original rotor and subtracting the missing material based on the cast allowed a finite element model to precisely image the geometry of the damaged rotor to be built (Figure 7).

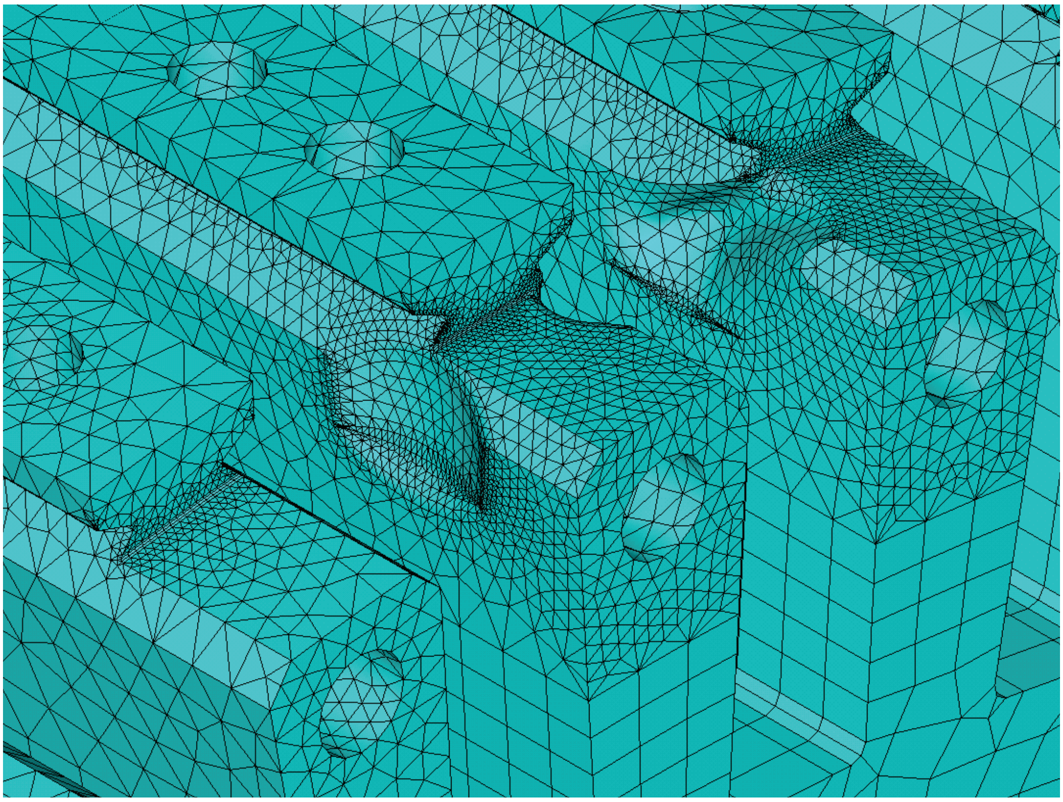

Figure 7: Finite-element-model of rotor shrink seat area showing the area with the removed material and the re-machined surfaces

Using Sensoplan's extensive experience in the field of generator calculations, the mechanical stresses in the rotor during operation, start-stop and faulty conditions could be determined quickly. The results were promising. Although, notch stresses exceeded the allowable values, the overall results indicated the possibility of successful repair by removing the damaged material.

Sensoplan rotor designers and machining specialists set out a plan for precisely how and where the melted material on the retaining ring and rotor should be removed. The most challenging boundary condition for this work was that the field winding had to stay in place, since a rotor rewind would have extended the forced outage time by several weeks and would have made the repair economically unattractive.

Sensoplan engineers finished the analysis and repair proposal in less than two weeks. Based on this work, the company was able to commit to a firm schedule for the customer and, most importantly, accommodate the delivery time for the damper system. After presenting the repair proposal to the customer and getting their approval, work started immediately.

Repair work

First, the winding was completely sealed off to avoid contamination with iron particles. In a repeating process, melted and cracked material was removed by milling and grinding, and dye-penetrant testing was performed on the newly machined and cleaned surface until no further crack indications were found. Casts were taken to capture the modified geometry. These were scanned and fed into the finite element model for recalculation. This allowed the identification of locations with stress raisers and to selectively re-machine these areas until the stresses were well below the allowable limit.

Figure 8 displays the distribution of the mechanical stresses in the teeth labelled 1, 2 and 3 at standstill when loaded with shrink forces. For better visualization of the rotor stresses the retaining ring is not shown. In the model the shrink forces are produced using contact elements in the entire shrink seat area between rotor teeth and retaining ring and applying an interference fit representing the true shrink fit dimension.

Tooth no.1 in figure 8 was not machined and still possesses its original geometry. In tooth no.2 and no.3 material was removed and they were re-machined to a new geometry at the transition between shrink seat and slot wall. Each tooth is subject to the same shrink forces. When the stress patterns for all 3 teeth are compared the differences are very small. This result reveals that the removal of the material did not create significant additional stresses. The stress level in the modified rotor is nearly the same as in the original rotor.

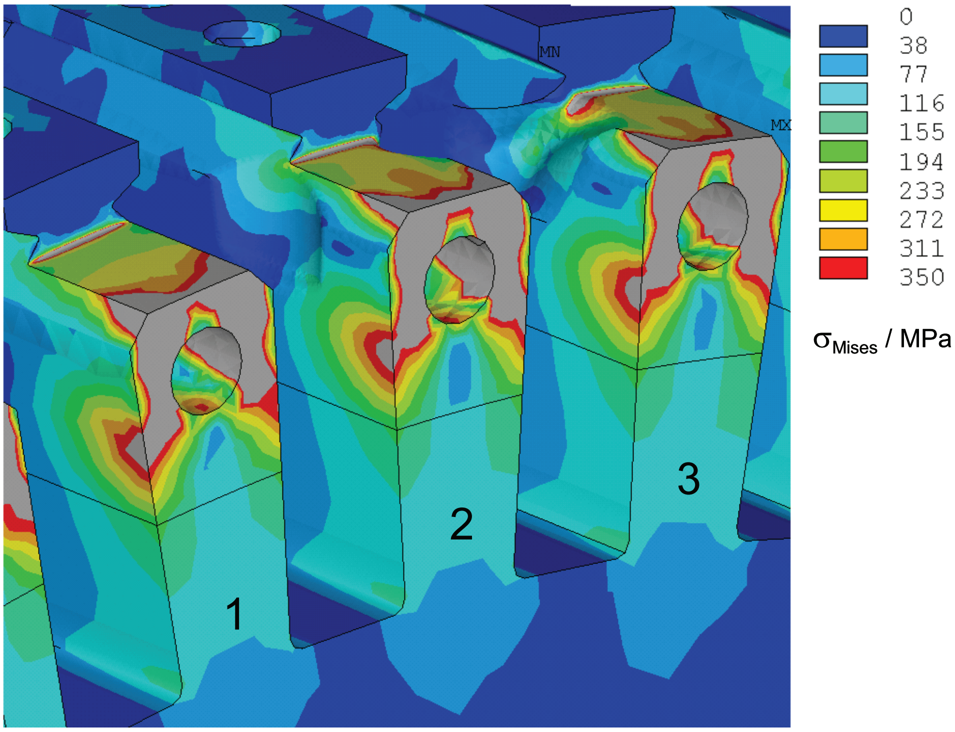

Figure 8: Finite-element-model of rotor shrink seat area showing the area with the removed material and the re-machined surfaces

After the final geometry was machined, extended eddy current testing was performed to ensure the rotor forging and the retaining ring were defect free. In addition, hardness measurements and high-resolution surface replicas were taken for microscopic analysis. The results confirmed that the strength and the microstructural properties (grain size and structure, precipitation size and density) showed no deviations from the original condition.
Based on the finite element calculations and the concluding microstructural analysis, the rotor could be re-qualified for a remaining lifetime of a further 2500 start-stops.

Reassembly of the rotor, balancing, and electrical and mechanical tests concluded the repair work.

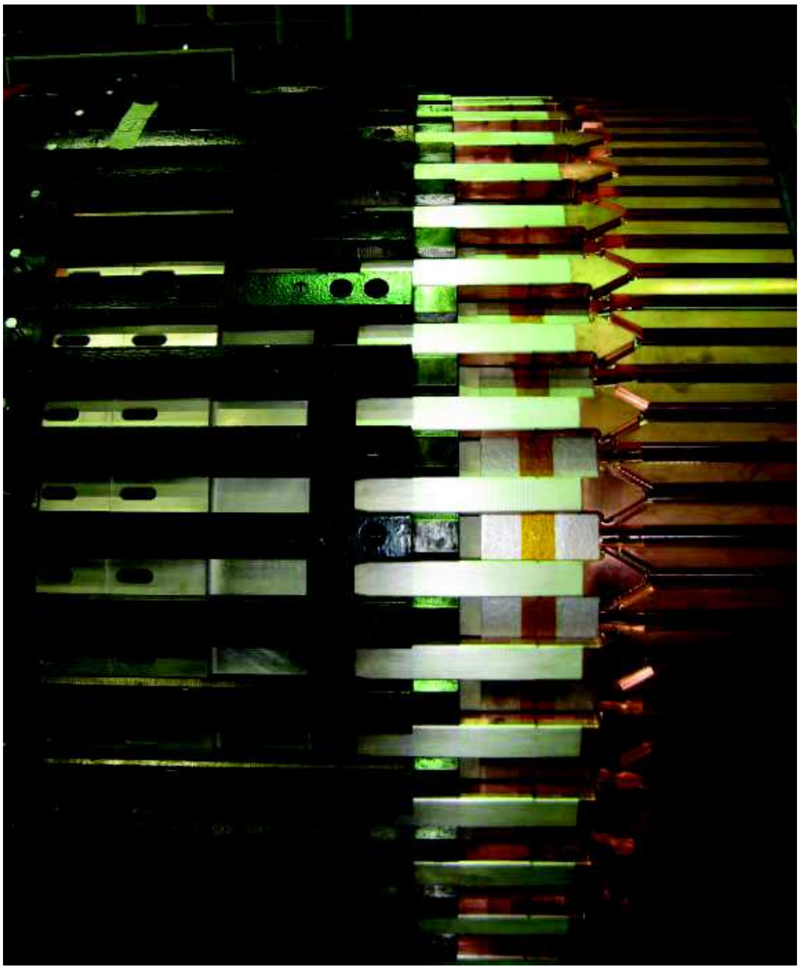

Figure 6: Reassembly of damper basket NDE, silver-coated damper fingers slide to the left on top of silver-coated damper bars

Operational behaviour after repair

After installing the rotor and recommissioning the generator power plant management decided to perform a final sustained short-circuit test (test B) as acceptance test. The results are presented in figure 9. Test B was carried out between 19:35:00 and 20:25:00 on 25.08.2008. The stator current was increased in three steps from about 6.500 A (50% of rated load) via 8.300 A (65% of rated load) to 12.000 A (93% of rated load). Up to 65% of rated load the vibration level was hardly affected by the damper current (30 to 37 µm 0-peak at generator NDE) whereas prior to the repair a steep, six fold increase was observed. Near rated load the vibration amplitude reached a value of about 80 µm and was well within the acceptable limit according to ISO 7919:2. The tremendously reduced vibration levels confirmed the success of the generator rotor repair.

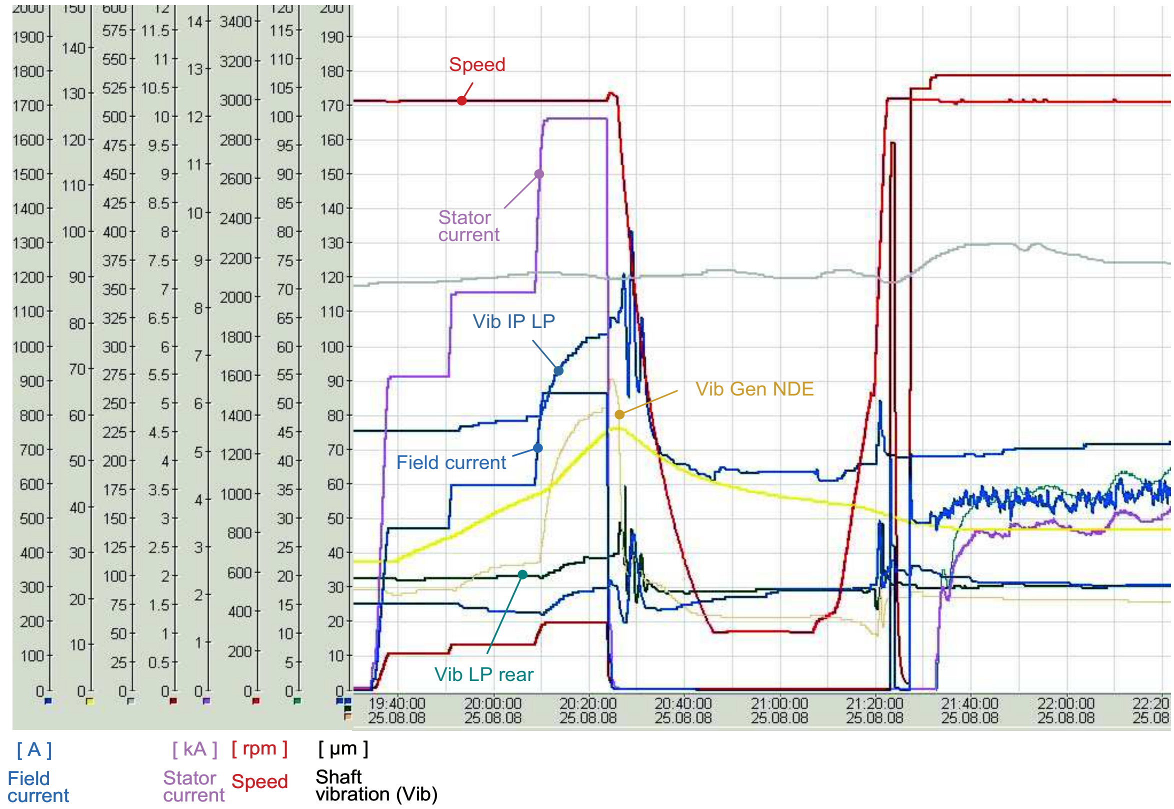

Figure 9: Sustained short-circuit test after repair, max stator current at 93% of rated value

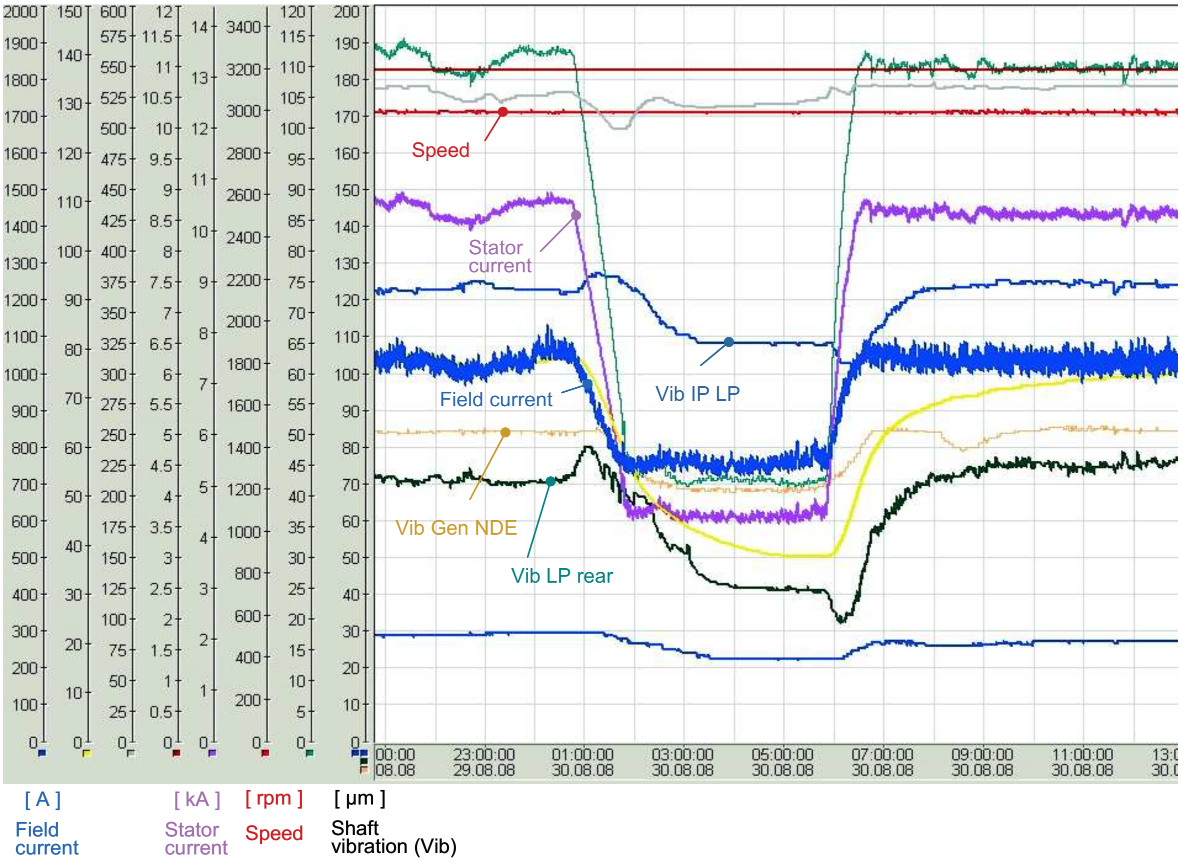

Figure 10: Load drop test after repair from nearly 100% down to 35% rated value

Figure 10 shows the results of a load drop test performed during operation on 30.08.2009. The generator load was reduced from nearly 100% down to 35%, kept at 35% for about 4 hours and raised back to full load afterwards. The influence of the load drop on the shaft displacement amplitudes is small and within the normal range for unrestricted long-term operation.

Conclusions

The project began with the task of refurbishing a 39-year-old, 110-ton generator rotor with a broken damper system, as well as other severe damage. The challenge of restoring continued unlimited operation quickly increased the difficulty of the task.

Taking into account these demanding conditions, E.ON placed the complete project with Sensoplan because of their well-known high-tech engineering and manufacturing services for turbo machines.

At the workshop, the project was executed in three major steps:

- Identification of the cause of the rotor defects and of the rotor vibrations: 14 broken damper fingers were detected. The imposed damper current bypassed the broken fingers by creating electrical arcs, leading to the melting of copper and steel at several locations. These hot-spots in the pole zone produced bending moments acting on the rotor, causing unbalanced conditions. The damper current and the hot-spot temperatures are functions of the generator load: the higher the load, the higher the vibration level. It was precisely this behaviour that was observed during plant operation.
- Analysis of the damaged zones through non-destructive testing and the taking of surface replicas for microstructural analysis, resulting in the proposal that the rotor could be repaired within the given time limit, despite considerable additional repair requirements and the fact that the field winding had to remain in place.
- Re-design of areas with identified stress raisers, by using the finite element calculation method, until all stresses were below allowable limits. The rotor forging and the retaining ring were eddy current and hardness tested.

Despite finding considerable further damage that required a great deal of additional work, the rotor was completed by the originally scheduled date with the help of modern fabrication and analysis methods. The rotor is now back in operation and has been running for several thousand hours at a drastically lowered vibration level and without operational limitations.

This project demonstrates that even old units with severe damage can be completely refurbished at an attractive price and within a set time frame.