

ACTIVE DAMPING OF TORSIONAL MODES IN TURBINE-GENERATOR SHAFTS

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Abstract – Subsynchronous resonance (SSR) may possibly occur in turbine-generators with long shafts and large inertias constituting a weakly damped mechanical resonator. Although SSR is most frequently encountered in power systems with series compensated transmission lines, electro-mechanical resonances can occur in all kinds of power systems where synchronous generators supply critical loads. Any load causing active power fluctuations with frequency components in the same range as the mechanical resonant frequencies of the generator shaft assembly can be critical. Evidence for this statement is supplied by measurements which were performed with a 144 MVA and a 220 MVA flywheel generator of the IPP experimental power supply. Subsynchronous oscillations and resonances were caused in the shaft assemblies of these synchronous machines by thyristor converter loads supplying an experimental tokamak. The problems could be solved in applying a compact damper circuit which is connected in parallel to the dynamic loads. This novel damping method has been continuously applied at IPP in more than 3000 dynamic load sequences. Since it has proven to be very efficient and reliable, this paper presents results from numerical investigations on applying this active damping method as a countermeasure to SSR in large electrical networks.

1. INTRODUCTION

Torsional resonance problems are most frequently encountered in rotor systems with long shafts and large inertias constituting a weakly damped mechanical resonator which exhibits a low (subsynchronous) resonance frequency, e. g. 20 – 40 Hz. Subsynchronous resonance (SSR) phenomena in electric power systems have received great attention in literature since the first two shaft failures in large turbo-generators in 1970 and 1971 [1-2]. Although SSR is usually discussed in case of systems with turbine generators and compensated transmission lines, it has been shown that this phenomenon can also occur in other cases, where it can also cause severe damage to machines and equipment [3]. Any load causing active power fluctuations with frequency components in the same range as the mechanical resonant frequencies of the generator shaft assembly can be critical. Evidence for this statement is supplied by

measurement results from the IPP experimental power supply, a 500 MVA power supply based on large flywheel generators.

As a countermeasure to these torsional resonance problems a novel feedback controlled circuit was developed for damping the torsional oscillations [4-5]. Connected to the stator winding of a synchronous machine it produces the same effect as an increased natural damping for oscillation modes in the rotating shaft assembly. Therefore, it can be universally applied to torsional resonance problems in electric power systems.

The paper is organized as follows. It starts with a description of problems with torsional oscillations which were experienced in the shaft assemblies of flywheel generators belonging to the experimental power supply of ASDEX Upgrade (AUG), Germany's largest experiment for nuclear fusion research. A parallel connected circuit developed for damping these subsynchronous oscillations is described in Section III and application examples are given. In Section IV a further developed design of the active damping circuit is presented. It is capable to actively damp torsional oscillations in multi-mass systems, e. g. turbo-generators with large shaft assemblies featuring several natural frequencies. The simulation results presented show that this damping circuit can even be applied to classical SSR problems, i. e. systems with turbine generators and compensated transmission lines. The paper ends with a conclusion on the simulation and test results achieved with this novel damping method.

2. TORSIONAL RESONANCE PROBLEMS IN THE IPP POWER SUPPLY

The active damping method for torsional oscillations in generator shaft assemblies was devised to solve problems which were experienced in the power supply of the ASDEX Upgrade (AUG) tokamak. The power and energy for the plasma experiments conducted with this experimental tokamak are supplied by large flywheel generators as shown in Fig. 1, the biggest of which can deliver a

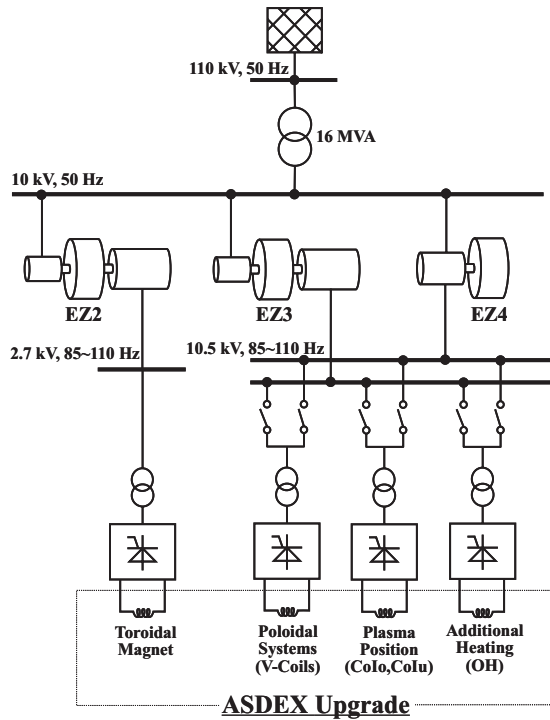


Fig. 1. Flywheel generator power supply of AUG tokamak

power of 150 megawatts for ten seconds with a flywheel weighing 230 tons. The flywheel generators supply high-power thyristor converters. They enable a fast control of the DC currents in the magnet coils used for magnetic confinement of the plasma in the static and dynamic case [6]. Because of problems with electromechanical resonances leading to a damaged coupling in the shaft assembly of the EZ4 generator, torque measurement and protection systems were installed (see Fig. 2). The torque measuring concept is based on the anisotropic magnetostrictive effect in ferromagnetic materials which is measured by a contactless inductive sensor [7]. A measurement result

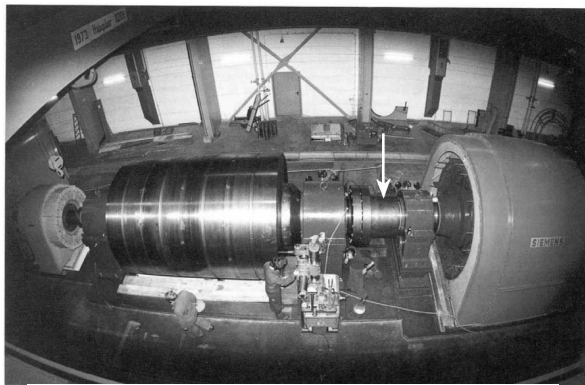


Fig. 2. One of the flywheel generators at IPP with the big flywheel in the middle and the generator on the right. The arrow shows where the torque sensor was installed on the rotor shaft system

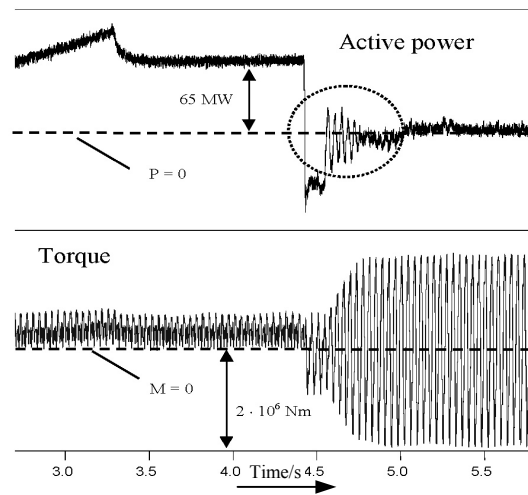


Fig. 3. Measured output power and torque at the rotor-flywheel coupling of generator EZ4

showing a resonant excitation of the EZ4 shaft is shown in Fig. 3. More than 100 electromechanical resonances occurring during plasma experiments were investigated by measurements and partly by numerical investigations. Many plasma experiments had to be prematurely terminated by the generator protection system in order to prevent negative effects on the durability of the shaft assemblies. A torque reduction by a factor of two could be achieved by a solution based on changing parameters of the plasma control system [8]. Since this solution adversely affected the dynamic performance of the control system [6], an effective method of damping the torsional resonances in the affected rotor shaft systems had to be developed.

3. DESIGN OF THE ACTIVE DAMPING CIRCUITS APPLIED AT IPP

Torsional oscillations in shaft systems can be described by the following n-dimensional differential equation system:

$$J\ddot{\phi} + D\dot{\phi} + K\phi = Bu \quad (1)$$

where

- $\phi(t)$ torsion angles of the shaft;
- $u(t)$ externally applied torques;
- J matrix of moments of inertia;
- D damping matrix;
- K stiffness matrix;
- B input matrix for external torques.

Since the damping matrix of a steel shaft system is more or less a fixed parameter, the method is based on applying an additional electrical torque through the stator winding, thus causing the same effect as one (or more) increased damping coefficient(s). In order to damp only one natural frequency of a shaft assembly,

this can be realised in applying an electrical torque in counter-phase to the measured torsional velocity of the shaft as illustrated in the block diagram in Fig. 4. The torsional velocity is electronically derived from the existing torque sensor measurement in the block "Control System for Signal Modification". Below that block, the feedback signal is superposed to a static value controlling the DC current in the inductor by means of a thyristor converter (current controlled six-pulse bridge circuit). The inductor is used as a buffer storage for magnetic energy, being loaded and unloaded in counter-phase to the torsional velocity of the shaft at the location of the torque sensor. Since the active damping circuit generates a damping power P_{damp} respectively an electromagnetic torque acting on the rotor with a frequency corresponding to the resonant frequency, this damping method is very efficient.

Once all control parameters are properly set, such a parallel connected circuit can be continuously used to damp one torsional mode of oscillation efficiently. Since the feedback control is based on a torque measurement, the damping effect is independent of the excitation curve (e. g. an electrical or a mechanical disturbance, pulse type loads or an active power oscillation). Different load curves do not require adjustments or modifications to control parameters of the damping module.

Since installation of the first active damping circuit in the ASDEX Upgrade power supply, this damping method has been continuously applied to two different synchronous machines in more than 3000

dynamic load cases up to now. A typical result from operating the active damping circuits during ASDEX Upgrade plasma experiments is shown in Figs. 5 (a) and (b). These curves were measured during the plasma experiments # 16971 and # 17779. In both cases the experiments were performed at a plasma current of 1.2 MA and they caused comparable load curves (EZ3 active power). Due to the low damping of the shaft assembly, an active power oscillation with a frequency of 24 Hz and a power in the order of 1 MW can cause the increase of the torque amplitude shown in Fig. 5 (a), reaching a value of 1.11 MNm. That value corresponds to an active power of 175 MW at a generator speed of 1500 r.p.m and caused the EZ3 torque sensors to send a trip signal. I. e. plasma experiment # 16971 was prematurely terminated because of a subsynchronous resonance. In Fig. 5 (b) active damping was provided by means of a parallel connected damping circuit with a 1 mH-inductor. As can be seen at $t < 0$, a high converter output voltage was only measured during ramp-up of the DC current in the damping circuit. Despite the low damping power used, the torsional resonance could be suppressed without problems. A DC current of 5 kA was flowing in the 1 mH-inductor of the damping circuit, i. e. the magnetic energy stored in the inductor was only in the order of tens of Kilojoule. However, the circuit provided sufficient damping power for this torsional resonance phenomenon in the EZ3 shaft assembly which weighs more than 100 tons. Main reason for this is the high Q-factor of the first torsional mode of the

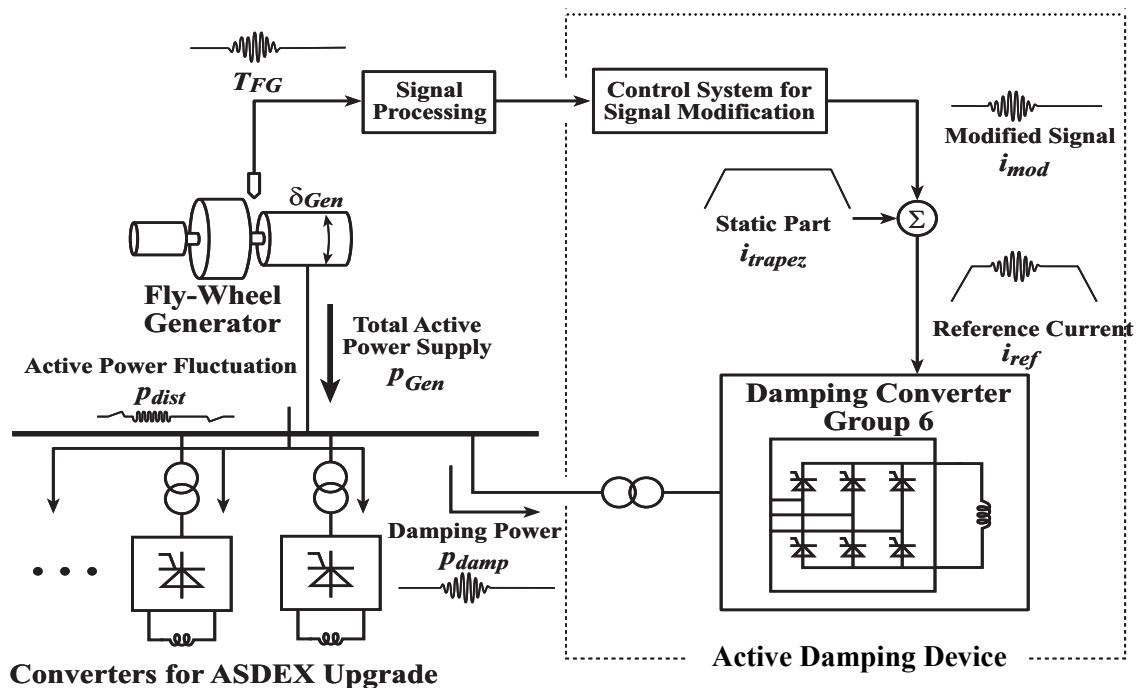


Fig. 4. Schematic of a thyristor controlled device for damping one torsional mode of a shaft assembly

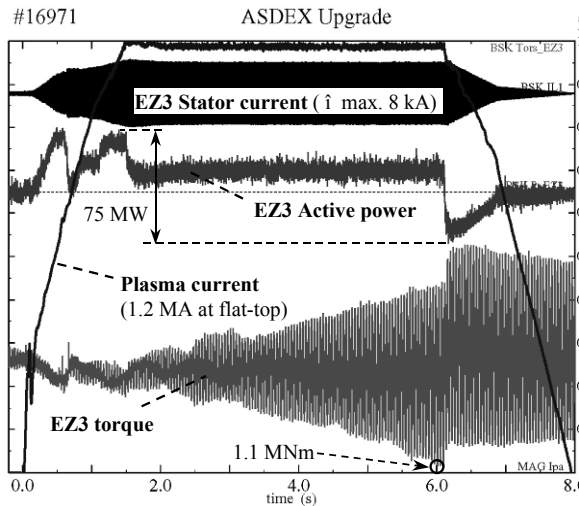


Fig. 5 (a) Measured EZ3 generator current, active power and torque showing a torsional resonance excited by power transients during ASDEX Upgrade plasma experiment # 16971

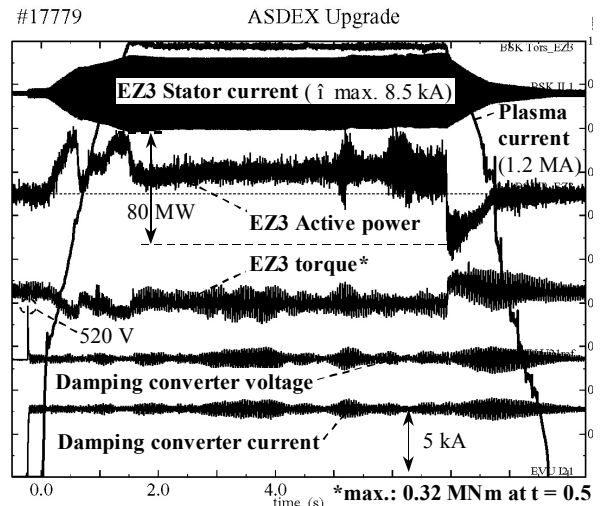


Fig. 5 (b) Suppression of a torsional resonance caused by a plasma experiment comparable to # 16971 in using an active damping circuit at low operational gain (damping power < 1 MW)

shaft assembly and the fact that the circuit generates a damping power of defined frequency which corresponds to the natural frequency of this mode.

The thyristor controlled damping circuits installed at the busbars of the IPP flywheel generators are operated at low gain of the control circuit and the damping power has been limited to a few Megawatts because this provides sufficient damping for the experiments performed on ASDEX Upgrade. Stability analyses, parametrical studies and tests have shown that this damping method can also be applied if a higher damping power or a high operational gain is required.

4. ACTIVE DAMPING OF SSR IN LARGE POWER SYSTEMS

For applications in large power systems, i.e. for damping a subsynchronous resonance in the shaft assembly of a turbo-generator, a damping power higher than the one applied at IPP is necessary and the active damping circuit must be capable to damp several torsional modes. Applying this damping method to a large turbo-generator requires a further developed design of the control module of the active damping circuit. A six-pulse thyristor bridge is sufficient for this type of application because the most relevant torsional modes of turbo-generator shaft assemblies correspond to resonant frequencies below the synchronous frequency (50 or 60 Hz). Fig. 6 shows an example design for a shaft assembly of a turbine-generator (IEEE Second Benchmark Model for Computer Simulation of Subsynchronous Resonance [9]). The turbine-generator has a nominal power of 600 MVA and a nominal voltage of 22 kV. The main

components of the shaft system are the exciter, the generator, a low pressure turbine (LP), and a high pressure turbine (HP). The torsional mode natural frequencies of this shaft system are:

$$f_{nat} = 24.65; 32.39; \text{ and } 51.1 \text{ [Hz]}.$$

The Second Benchmark Model for SSR simulations represents a more common type of power system than the First Benchmark Model. The Second Benchmark Model consists of the single generator shown in Fig. 6 which is connected to two lines, one of which is series compensated. A compensation value of 55 % has been chosen in the compensated line since this provides the best tuning for the first torsional mode. In order to avoid that the simulation results are affected by too optimistic assumptions for the torsional mode damping, damping coefficients were applied which were derived from measurements performed at IPP (which represent the torsional mode damping of shaft assemblies in the no-load case). In literature, the simulations are usually performed with much higher damping values in order to achieve that the simulation model is steady-state stable when the fault occurs [9]. As can be seen in Fig. 7, a compensation degree of 55 % of the series compensated transmission line leads to a self-excitation of the configuration in Fig. 6 if low damping values are assumed which are realistic in the no-load case.

In order to study a critical case of torque amplification, a three-phase fault (short-circuit) on the high side of the generator step-up transformer is applied, the fault clearing time is assumed to be 40 ms. At this duration of the fault a simultaneous excitation of the first and second torsional modes of the shaft assembly occurs, leading to high shaft torques at the couplings HP-LP and GEN-LP. In order to enable a

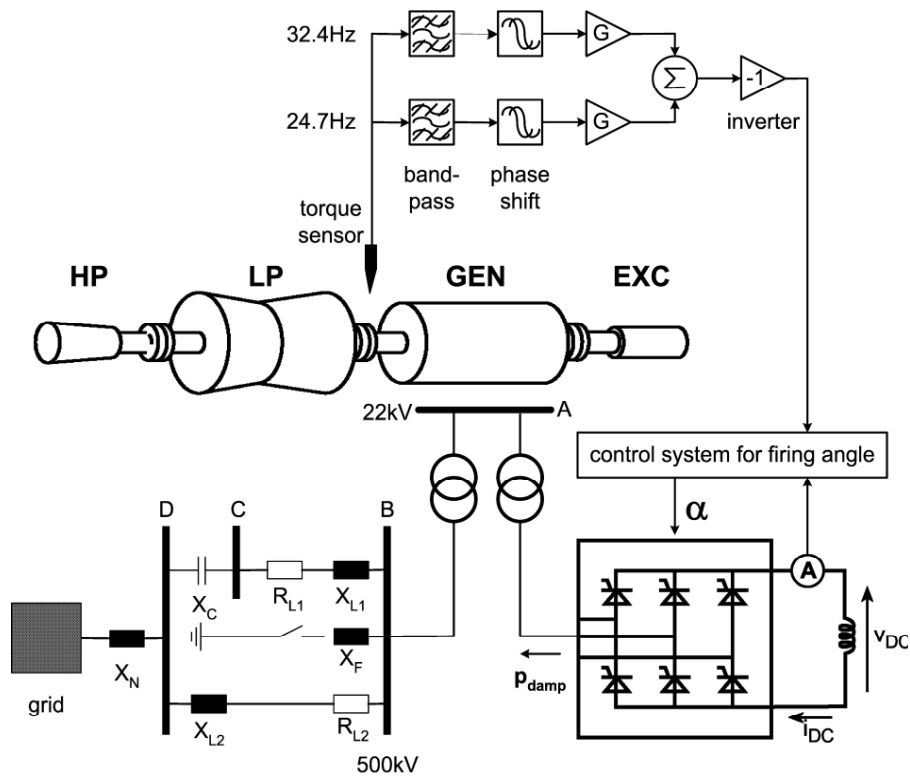


Fig. 6. Electrical network representation of IEEE Second Benchmark Model for SSR simulations and active damping circuit for a turbine generator (with an extended control module for the multi-mass system)

better comparison with the simulation results in literature [9], the first curve in Fig. 8 is given in per-unit values whereas the second curve shows the GEN-LP shaft torque in MNm during the first two seconds after occurrence of the fault, if no active damping is applied. The third curve in Fig 8 shows the active power which is exchanged between the turbine generator and the 500 kV network.

In Fig. 9 the same parameters concerning the model and the fault were applied but the active damping circuit shown in Fig. 6 was activated at occurrence of the fault. The two upper curves show the GEN-LP shaft torque and the HP-LP shaft torque in MNm during the first two seconds after occurrence of

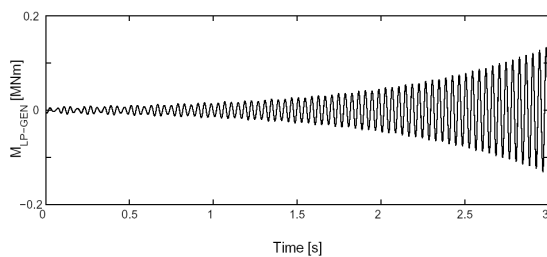


Fig. 7. Self-excitation of the configuration shown in Fig. 6 (without active damping)

the fault. The third curve is the active power which must be generated by the damping circuit in order to damp the resulting torque values. It can be seen that a peak damping power of 20 MW for less than two seconds is sufficient to damp this subsynchronous resonance phenomenon and to limit the maximum torque in the shaft system to values below 3 MNm. The damping circuit also suppresses the self-excitation of the turbine-generator which requires a damping power of less than 100 kW (less than 10 kW in the steady-state).

20 MW is only the maximum short-time power such a parallel damping circuit must provide. The nominal power of the circuit can be a factor of four lower than that (i. e. the active damping circuit can be designed for a continuous rating of 5 MW). Therefore, this damping method is not only attractive for power systems with special load requirements such as in the experimental power supply of IPP. This damping method could also be applied to turbine generators in order to protect them from subsynchronous resonance. Since this protection is achieved in simply increasing the torsional mode damping as given by Equation (1), i. e. without having to consider the state of the power system supplied by the the turbine-generator, the parallel connected damping circuit may be an attractive alternative to existing SSR countermeasures.

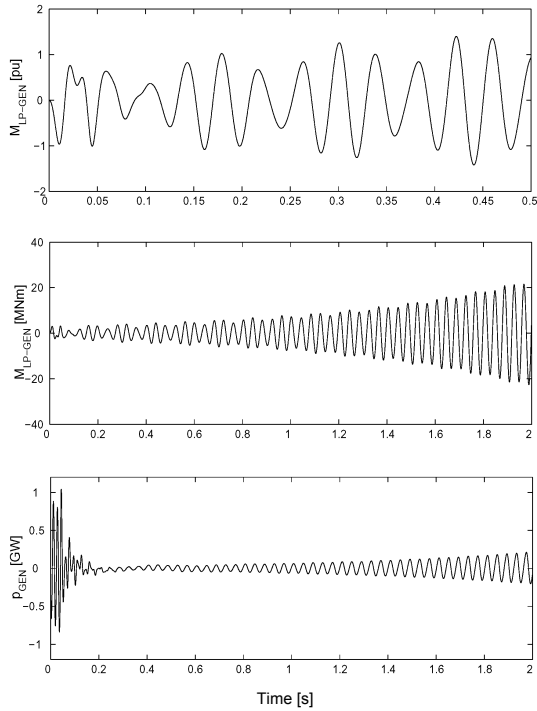


Fig. 8. SSR excitation in the Second Benchmark Model (three-phase fault, clearing time 40 ms): GEN-LP shaft torque (upper two curves) and turbine-generator active power

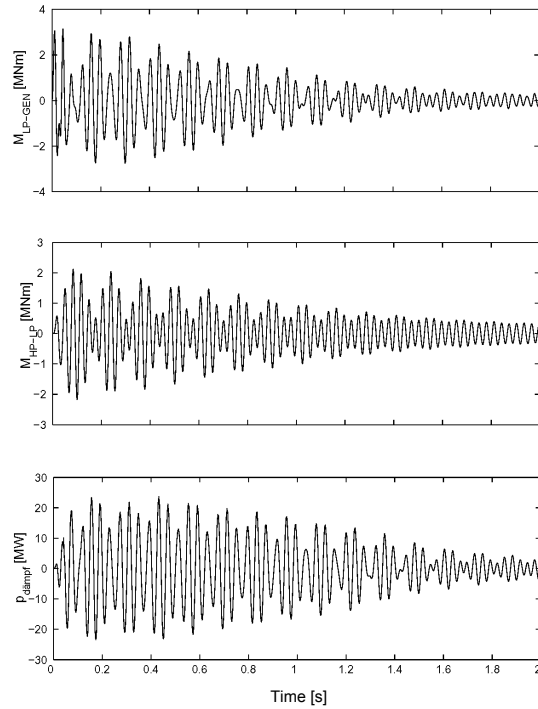


Fig. 9. Active damping of SSR case shown in Fig. 8 (damping circuit configuration as shown in Fig. 6): GEN-LP, HP-LP shaft torque (upper two curves) and active power generated by the damping circuit

5. CONCLUSIONS

A thyristor controlled circuit for damping subsynchronous oscillations in the shaft assembly of synchronous generators has been developed, installed, tested and continuously operated in the pulsed power supply of a tokamak experiment. Connected to the stator winding of a synchronous machine, the damping circuit produces the same effect as an increased natural damping of torsional modes in the rotating shaft system. The novel damping method has proven to be very efficient and reliable in more than 3000 dynamic load sequences occurring at a 144 MVA and a 200 MVA flywheel generator. The nominal power of the active damping device can be up to 100 times lower than the nominal power of the driving shaft, thus enabling a compact and cost-effective design.

Numerical simulations on applying this damping method to large turbine-generators were performed in order to investigate its suitability to damp SSR. They show that this damping method can also be applied to large power systems and multi-mass shaft assemblies. It may be an attractive alternative to existing SSR countermeasures because the active damping circuit can be installed at medium voltage level and does not require modifications in the existing power system.

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