Damping of Torsional Resonances in Generator Shafts Using a Feedback Controlled Buffer Storage of Magnetic Energy

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Abstract – **The power and energy for ASDEX Upgrade, Germany's largest experiment for nuclear fusion research, is provided by three separate networks based on flywheel generators. Damage at couplings of the shafts of the flywheel generators EZ3 (144 MVA / 500 MWs) and EZ4 (220 MVA / 600 MWs) were discovered during a routine check. They can only be explained by subsynchronous resonances (SSR) which are excited by active power transients from the converter loads. Torque sensors were installed for generator protection. They cause an early termination of plasma experiments if a predefined torque level is exceeded. Since the low natural damping involved with torsional resonances was identified as a major cause of the SSR phenomena observed, two feedback controlled DC circuits were developed providing electromagnetic damping for the generator shafts in case of SSR excitation. Since April 2003, the damping circuits have been routinely operated during all plasma experiments. They provide sufficient active damping power to avoid a trip signal from the torque sensors. The paper summarises results from analysing, designing, commissioning and operating these damping circuits which might be of general interest since they are an effective and low cost solution for damping SSR in electric power systems.**

Keywords – Subsynchronous resonance (SSR), torsional oscillation, active damping, damping control, magnetic energy storage

I. INTRODUCTION

The ASDEX Upgrade (AUG) tokamak, a nuclear fusion experiment [1], requires electrical power up to a few hundred megawatts for a time period of about ten seconds. The power and energy is provided by three separate networks based on flywheel generators [2, 3], as shown in Fig. 1. In 1999, during a routine check performed on generator EZ3, it was discovered that the coupling bolts of the flywheel-generator shaft were deformed. In 2002, damage was also discovered during inspection of a coupling of the EZ4 shaft assembly. Given that the active load of each generator in service (~100 MW) is well below the design value of the shaft (> 800 MW), the damage can only be explained by a torsional resonance of the shaft, itself excited by active power transients from the converter loads.

Values of 23.8 Hz and 26 Hz were calculated for the first natural frequency of the EZ3 and EZ4 shaft assembly. Frequencies between 10 and 30 Hz have been identified in the spectrum of the ASDEX Upgrade load curves. Since torsional shaft oscillations are characterised by very low damping, torsional resonance can become dangerous even for over-dimensioned generator shafts. Therefore, in 2001, contactless torque measurement systems [4] were installed on the shafts of the EZ3 and EZ4 generators. The torque sensors were installed close to the coupling between the flywheel and the rotor. A measurement result showing a resonant excitation of the EZ3 shaft is shown in Fig. 2. Although the load curve (measured active power) shows no evident active power transients between t = 2 s and t = 6 s, the curve contains a spectrum of frequencies in the range 20 – 30 Hz which is caused by feedback control of the plasma [5]. The feedback control system serves to magnetically confine the plasma by means of magnet coils supplied by thyristor converters as shown in Fig. 1. Due to the low damping of the shaft, an active power oscillation with a frequency of 24 Hz and a power in the order of 1 MW can cause an increase of the torque amplitude as shown in Fig. 2 up to a value of 1.11 MNm. This 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 terminated early due to SSR. In order to exclude negative effects on the lifetime of the shaft system, low trip settings had to be applied, thus causing an early termination of many plasma experiments. Before protecting the machines in that way, torque amplitudes corresponding to an active power higher than 400 MW and 700 MW had been measured on the EZ3 and EZ4 generators [5].

During plasma experiments conducted in 2002, more than 100 SSR phenomena were investigated by measurements and partly by numerical investigations. The evaluation of the results showed that the main problems causing SSR at IPP are not the dynamic properties of the load (ASDEX Upgrade) but the low natural frequencies of the shaft systems and the low natural damping involved with torsional oscillations of the rotating parts of the machines. The high Q factor of the EZ3 shaft can be seen in the sharpness of the resonance point at 23.8 Hz shown in Fig. 3. Having investigated different methods of reducing the torsional stresses in the generator shafts by simulation and measurement, IPP decided to develop its own method of damping SSR. The object of the development was to install one feedback controlled damping circuit at each generator, therefore allowing one mode of torsional resonance to be damped efficiently. Conventional methods for damping SSR are either based on facilities enabling to control reactive power in order to increase the torsional mode damping (e. g. thyristor controlled series capacitor, shunt reactor or SVC), or provide damping by modulating the generator output power by means of power electronic devices in-

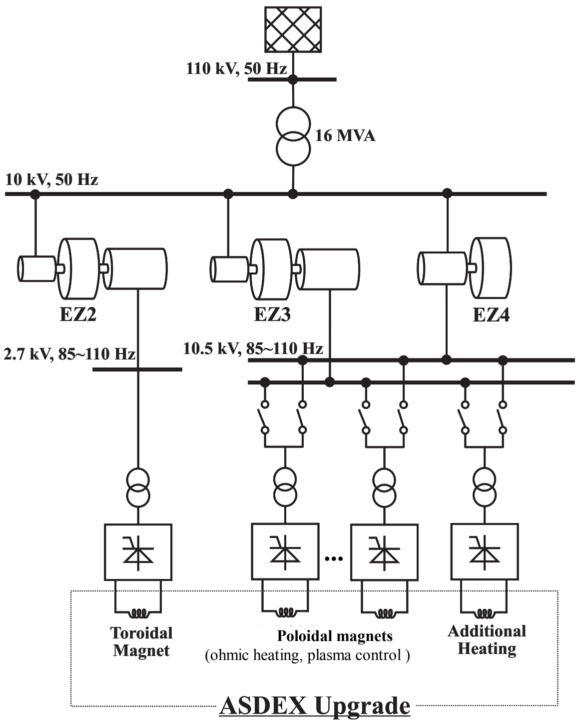

Fig. 1. Flywheel generator power supply of AUG

stalled in the network (e. g. FACTS devices). Like these devices, the IPP damping circuits were designed to damp torsional resonances by means of active power. However, a novel design of the damping system and control scheme was developed in order to fulfil the requirement of damping SSR without having to influence control parameters of the network or tokamak load (AUG). The new damping circuits are directly connected to the generator busbars and are operated independently from other devices or control systems. The active power required for damping SSR is provided by separate magnetic energy storage units as described in section II.

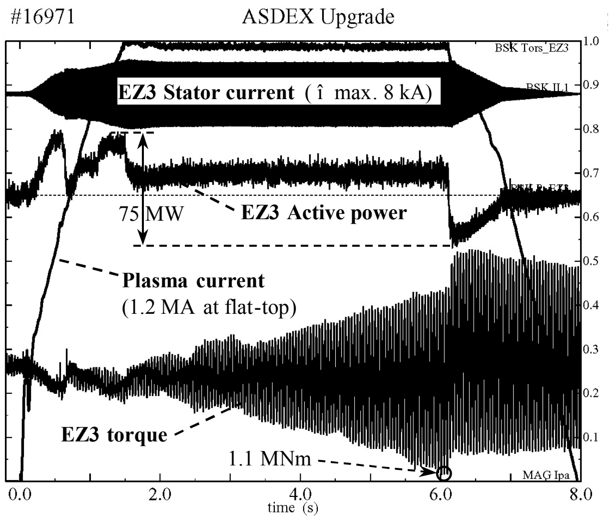

Fig. 2. Time histories of generator current, active power and measured torque during plasma experiment # 16971

II. Detailed Design of the IPP Active Damping Circuits

The use of energy storage devices, such as a superconducting magnetic energy storage (SMES) system, seems most attractive for damping SSR phenomena [6]. But in view of shaft assemblies weighing more than a hundred tons (e. g. EZ3 shaft system: 117 tons, EZ4 shaft system: 142 tons), the necessity of installing a sufficiently large energy storage unit is disadvantageous. For damping SSR phenomena as described in section I, it would be necessary to install an energy storage system capable of generating more than a hundred active power pulses with amplitudes of at least one megawatt. In view of the complexity and costs of a SMES or the technical and maintenance effort caused by other energy storage systems (e. g. based on batteries) a new approach for providing the active damping power was developed.

This approach is based on the classical damping method for a mechanical oscillator which can be used efficiently in taking advantage of the high Q factor of the torsional oscillation, as shown in Fig. 3. Generally, torsional oscillations of generator shafts can be described by the following n-dimensional differential equation system:

$$\boldsymbol{J}\ddot{\boldsymbol{\phi}} + \boldsymbol{D}\dot{\boldsymbol{\phi}} + \boldsymbol{K}\boldsymbol{\phi} = \boldsymbol{B}\boldsymbol{u} \tag{1}$$

$\boldsymbol{\phi}(t) \varepsilon \boldsymbol{R}^n$: Torsion angle of shaft; $\boldsymbol{u}(t) \varepsilon \boldsymbol{R}^n$: Torque; $\boldsymbol{J}$: Matrix of moments of inertia; $\boldsymbol{D}$: Damping matrix $\boldsymbol{K}$: Stiffness matrix; $\boldsymbol{B}$: Input matrix for electrical torques

The most efficient damping method is to apply an additional electrical torque in counter-phase to the torsional velocity $\dot{\phi}$ of the shaft. In general, the application of such a torque seems difficult. But having to deal with only one torsional mode [5] and having torque sensors installed which permit to measure the torsional stress (i. e. the torsion angle of the shaft) with high accuracy [4], meant that this approach seemed practicable. The torsional velocity is derived from the torque measurement. The derivation is realised in the block "Control System for Signal Modification" in Fig. 4 by means of a phase shifter. Considering all delay times in the feedback loop a total phase shift of 90 degrees is applied. The phase-shifted feedback signal (i_{mod})

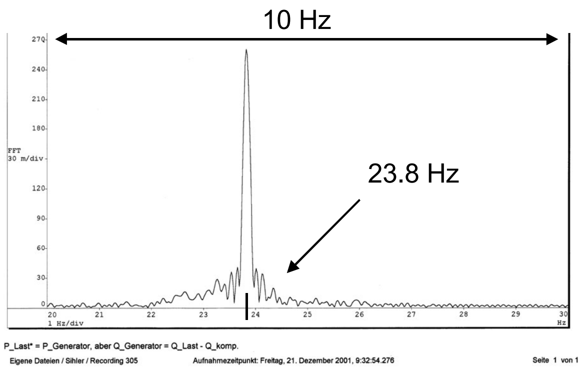

Fig. 3. Fourier analysis of EZ3 torque sensor signal

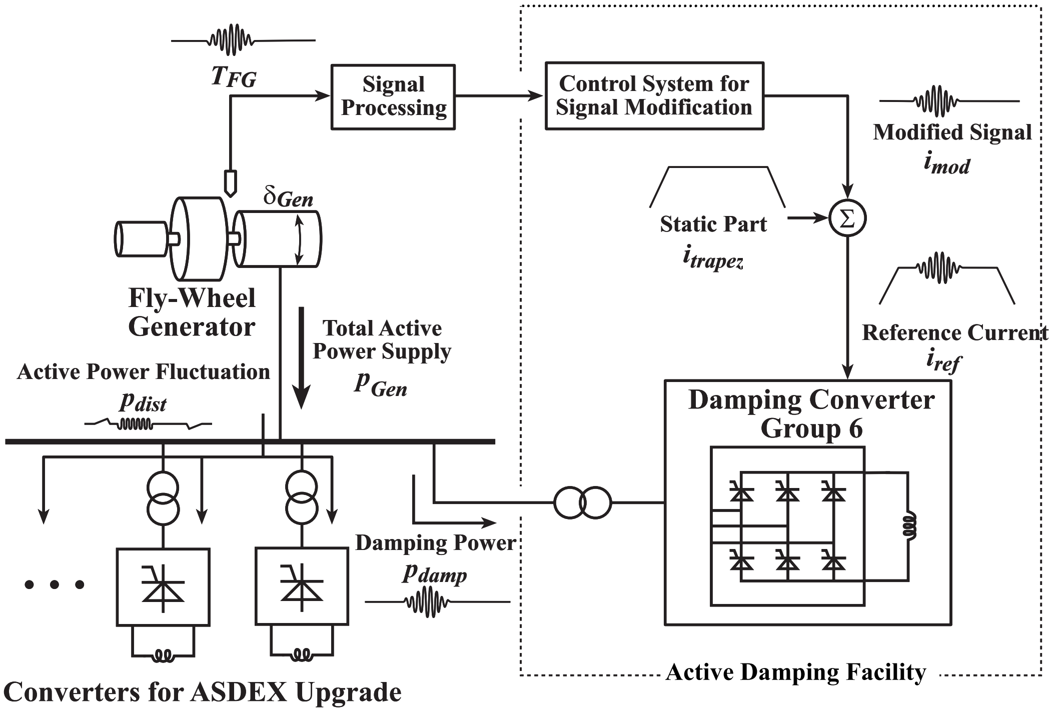

Fig. 4. Schematic of feedback controlled DC circuit for damping of torsional resonances in the EZ3 shaft assembly

is superimposed on a static value (i_{trapez}) controlling the DC current in an inductor which is supplied by a current controlled six-pulse thyristor bridge (damping converter).

The advantage of using a feedback circuit as shown in Fig. 4 is that the current flow in the inductor is controlled with a frequency corresponding to the measured natural frequency of the shaft assembly. Therefore, with proper phasing, only very little power must be applied in order to damp the torsional resonances. This allows a compact design of the damping system. The inductor is only used as a means for buffer storage of magnetic energy, being loaded and unloaded in counter-phase to the torsional velocity of the shaft. Only small inductance values are necessary in the DC circuit (a few millihenry), thereby allowing the circuit to be de-energised until torsional oscillations are detected. Actually no magnetic energy storage unit is required, only a compact buffer storage of magnetic energy. The magnetic energy stored in the active damping facilities installed at the EZ3 and EZ4 busbars is very low (tens of kilojoule). However, these circuits provide sufficient damping for the SSR problems experienced in the past. One reason for that is the steepness of the resonance curves of the problematic torsional modes, as shown in Fig. 3.

III. Simulation Model and Numerical Investigation of the Damping Circuits

During the development and construction phase of the damping circuits a numerical simulation model of the system shown in Fig. 4 was derived using the program package Simplorer [7]. The main purpose of the numerical simulations was to optimize operational parameters, perform parametrical studies and investigate the transient stablity of the set-up under normal operating and fault conditions. For these investigations a detailed model is required. Thus, the non-linear properties of the synchronous machines, the thyristor converters and the control system can be considered with sufficient accuracy.

A detailed investigation of the EZ3 shaft-system dynamics had already been performed [8]. The transient analysis of feedback controlled DC circuits for damping SSR required numerical simulations with coupled electrical, magnetic and mechanical variables. A simplified model of the EZ3 mechanical rotor-shaft system was developed for this purpose (see Fig. 5) and integrated into the generator model based on dq0 parameters [9]. The differential equation system of the mass-spring model was derived from single torque equations as given by equation (1) in the general case. If the natural damping of the mechanical system is neglected, the differential equation system can be resolved with additional variables as given in equation system (2). The natural damping of the shaft was modelled on

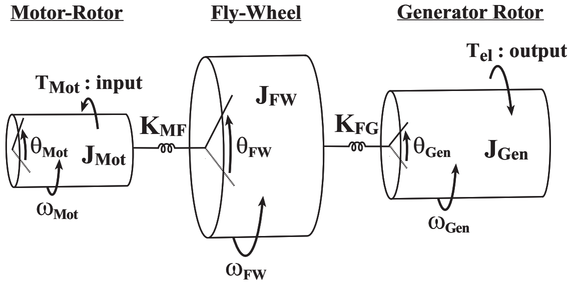

Fig. 5. Mass-spring model of EZ3 shaft system

$$
\begin{aligned}
\omega_{Mot} &= \frac{1}{J_{Mot}} \int (T_{Mot} - T_{MF})\, dt \\
\omega_{FW} &= \frac{1}{J_{FW}} \int (T_{MF} - T_{FG})\, dt \\
\omega_{Gen} &= \frac{1}{J_{Gen}} \int (-T_{el} + T_{FG})\, dt \\
T_{MF} &= K_{MF} \int (\omega_{Mot} - \omega_{FW})\, dt \\
T_{FG} &= K_{FG} \int (\omega_{FW} - \omega_{Gen})\, dt
\end{aligned}
\tag{2}
$$

T_{MF} : Torque excerted at shaft between motor-rotor and flywheel
T_{FG} : Torque excerted at shaft between flywheel and generator-rotor

the electric circuit representation of the mechanical model by means of ohmic resistances.

Since one purpose of the simulation model was to analyze all phase shifts and delay times in the feedback circuit, not only the synchronous machine including rotor-shaft system, but also the transformers, thyristor converters with control system and all electronic components of the feedback loop had to modelled in detail.

IV. TEST SET-UP FOR COMPARISON OF SIMULATION AND MEASUREMENT

A test configuration was set up in order to investigate the dynamic response of the damping loop and to commission the damping system at low power. In the test configuration the dynamic load (ASDEX Upgrade) was replaced by only one thyristor converter (“disturbance converter") feeding a magnet coil with an inductance of L = 34 mH. A defined excitation of torques in the generator shaft can be accomplished by means of dynamic control of the converter current, as shown in Fig. 6.

For damping tests the output power of the feedback controlled DC circuit can be reduced in two ways:

- Electronically (reduced gain in the feedback loop)
- By limitation of the DC current of the damping converter (in limiting the static reference i_{trapez}, see Fig. 4)

The latter is an important safety feature because limiting and monitoring the DC current of the damping converter permits fail-safe testing. An existing thyristor converter module of the ASDEX Upgrade power supply (U_{di0}= 1.5 kV, I_N = 22.5 kA) was used as a "damping converter". A water-cooled coil (L = 5 mH) was used as converter load in the damping circuit, i. e. as buffer storage of magnetic energy. During the tests, the DC currents were limited to low values (I < 6 kA) by means of reference limiting and a trip level based on a DC current measurement. Additional protection was achieved by means of two (completely) redundant torque measurement systems with fast-acting trip-levels. After adjustment of the hardware in the feedback loop and optimum setting of the phase shifter, the damping capability of the first active damping circuit was demonstrated by the end of January 2003, as shown in Fig. 7. The active power flow during the damping tests cannot be evaluated by measurement. It was evaluated by simulation,

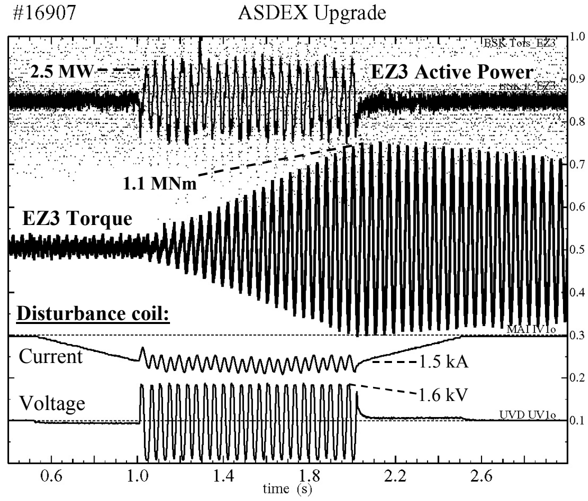

Fig. 6. Defined excitation of torsional resonance in the EZ3 generator shaft in controlling the current in the „disturbance coil“ with 24 Hz

as shown in Fig. 8.

Starting in February, the active damping circuit with the 5 mH-coil has been successfully used for SSR damping on generator EZ4 during all plasma experiments performed (active damping in more than 1000 loading cases since then). Despite the use of an active damping circuit on generator EZ4, dozens of plasma experiments still had to be interrupted because of a violation of the maximum allowed torque level in the shaft assembly of generator EZ3 (feeding a separate network as shown in Fig. 1). Therefore, a second active damping circuit had to be developed and installed in that network. Since a second magnet coil with parameters comparable to the first active damping circuit was not available, numerical investigations were performed in order to investigate the stability limits and operational restrictions if a much smaller inductance (1 mH) was used

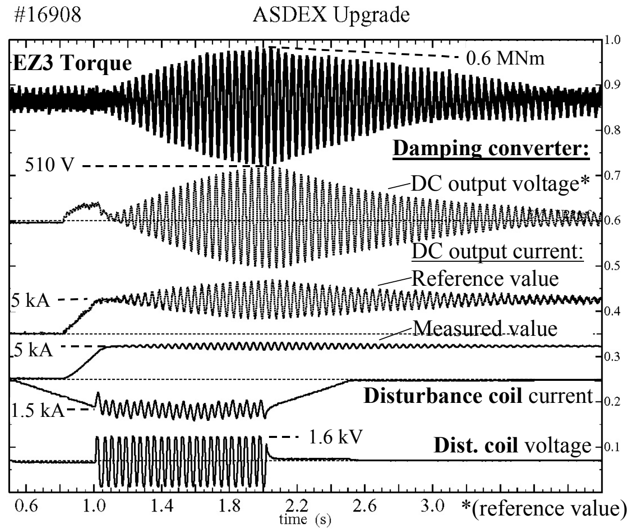

Fig. 7. Damping of the torsional resonance shown in Fig. 6 by means of active damping circuit operated at low power (< 2 MW)

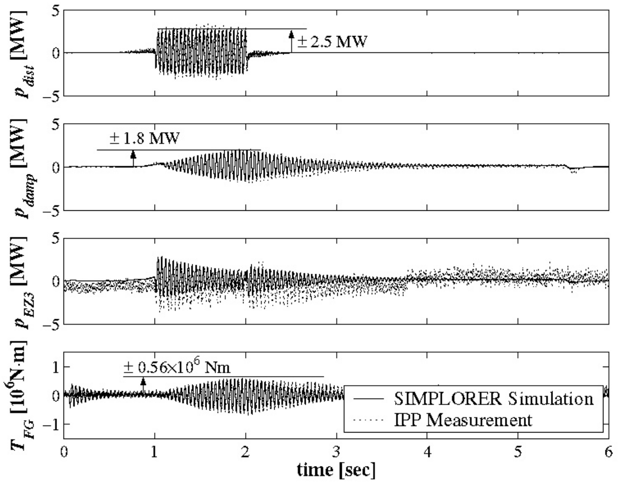

Fig. 8. Active power during the damping test shown in Fig. 7 (comparison of simulation and measurement)

as a buffer storage of magnetic energy. Since the simulations and additional tests showed that a damping power comparable to the first active damping power could be achieved in operating the second damping circuit more dynamically (higher gain in the feedback loop), the second active damping circuit was developed and installed using a 1 mH-inductor. As shown in Fig. 9, the damping properties of the second active damping circuit are comparable to those of damping circuit no. 1. This is remarkable because it shows that torsional resonances in a shaft assembly weighing more than 100 tons can be damped by means of a 1 mH-inductor, i. e. by means of stored energy of less than 25 kJ. Since inductors with small inductance values can be operated with high current ramp-up rates, the active damping circuit can be de-energised until a torsional oscillation is detected. As soon as torsional resonance is detected, the availability of the active damping circuit can be established within milliseconds.

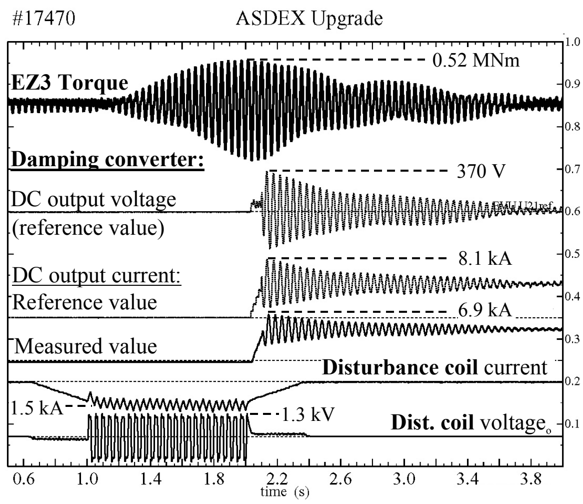

Fig. 9. Damping of torsional resonance (as in Fig. 6) with feedback circuit no. 2 (damp. coil with 1 mH)

V. DAMPING OF SSR DURING PLASMA DISCHARGES

Since commissioning of the second active damping circuit in April 2003, both have been continuously used during plasma discharges. Up to now (end of July 2003) the effectiveness and robustness of using this damping method has been proven in about 1000 plasma discharges. Examples of SSR damping during plasma discharges are shown in Figs. 10-12. Figure 10 shows torsional resonance damping on generator EZ4 after the occurrence of active power transients with an amplitude of more than 50 MW. They were caused by a scenario for ramping up the plasma current which was not optimal.

A more typical result from ASDEX Upgrade operation is shown in Fig. 12. These curves were measured in an experimental scenario which was very similar to the one shown in Fig. 2. Active damping was provided by means of damping circuit no. 2. 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, torsional resonances, as they are shown in Fig. 2, could be suppressed without problems.

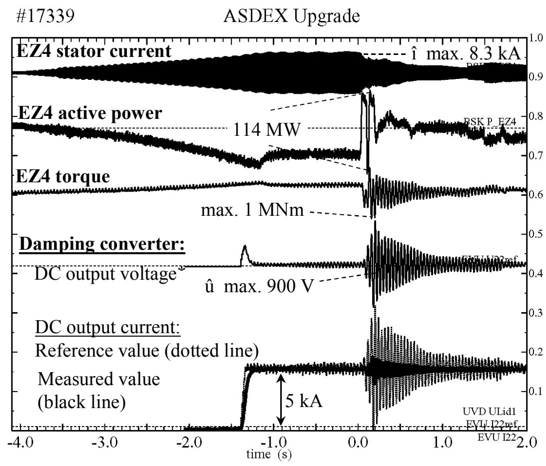

Fig. 10. Damping of SSR during plasma experiment (damping circuit no.1 - coil with 5 mH)

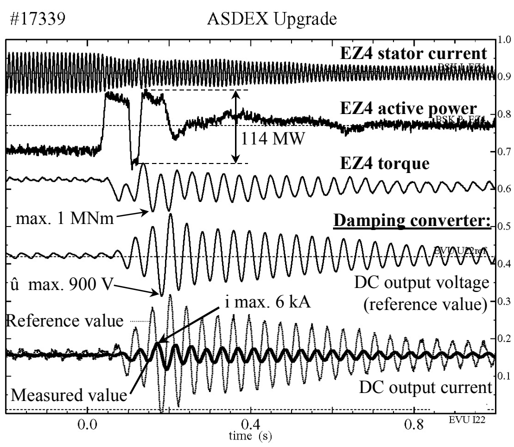

Fig. 11. Detail of Fig. 10

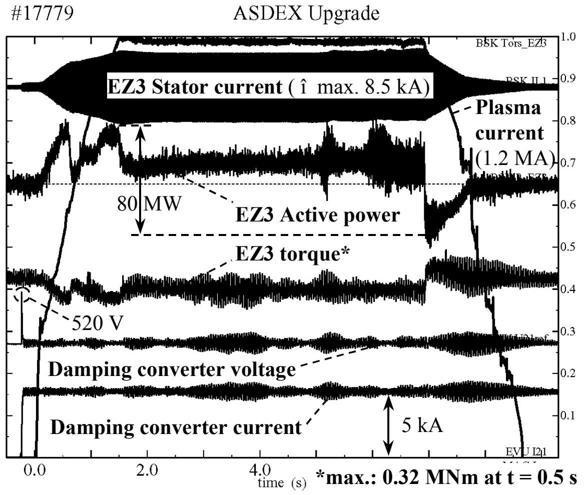

Fig. 12. Damping of SSR during plasma experiment (damping circuit no.2 - coil with 1 mH) – similar load curve as shown in Fig. 2.

The duration of the plasma experiment was not limited by torsional resonances, although more active power transients could be observed in the time history of active power (at t > 5 s) than in Fig. 2. They are caused by stability problems of one of the converters operated at high current (disturbance frequency > 30 Hz), whereas small disturbances with frequencies in the range below 30 Hz are mainly caused by plasma feedback control [5].

VI. Results of Parametrical Studies, Tests and Further Investigations

Parametrical studies show that the effectiveness of using a feedback controlled buffer storage of magnetic energy is not limited to low values of the inductor or converter output power. The simulations show that a damping power of more than 50 MW could be established in operating active damping circuit no. 1 at higher DC current (e. g. in using two converter modules in parallel), or at higher converter output voltage (e. g. in using two converter modules in series), therefore in principle, this damping system could also be applied to larger machines. More than one torsional mode can be damped if one active damping circuit is used for each torsional mode (to be measured by separate torque sensors along the shaft assembly). Since the damping circuits are operated at low power and generate only one frequency, they could ideally be used in networks supplied by several generators with different mechanical parameters.

At IPP the damping power has been limited to values below 10 MW because that has provided sufficient damping for all plasma experiments performed since January. In most plasma discharges, the feedback controlled damping power even stayed below 5 MW. Despite this power limitation, redundant and diversified protection systems were installed on both machines ensuring that a malfunction of the active damping circuits (working at the natural frequency of the 1st torsional mode), or a violation of the torque limits could be detected immediately and cause an action corresponding to the fault level. If, for example, the highest of three fault levels is reached (which has not happened so far), the feedback loop will be opened by means of hardware circuitry within milliseconds and a fail-safe signal causing an early termination of the pulse will be sent to all converter modules.

Further development work will be dedicated to a thermal optimisation of the damping circuits. This can be achieved in adding either a second feedback loop, or an additional control loop so that the static current reference i_{trapez} (see Fig. 4) can be controlled depending on the measured torsional amplitudes. This will allow an even more compact design of the active damping installation.

VII. Conclusions

Two novel systems for damping subsynchronous resonances in a separate network have been developed, installed, commissioned and operated this year. They are directly connected to the generator busbars and damp the first torsional mode efficiently, providing torques to the rotor-shaft system which have the same effect as increased natural damping. The active damping circuits are independently controlled by using the torsional stress measured by contactless torque sensors. The active power for damping the torsional resonances is taken from compact buffer storages of magnetic energy (stored energy < 50 kJ). They are loaded and unloaded with the natural frequency of the 1st torsional mode of the shaft assembly, thus providing sufficient damping power for SSR in generator shafts weighing more than 100 tons. The new damping circuits have proven to be an efficient and reliable method of damping SSR in hundreds of cases during plasma experiments which can cause torsional stresses similar to a static load with a magnitude higher than 700 MW.

References

[1] T. Hamacher, A.M. Bradshaw, "Fusion as a future Power Source: Recent Achievments and Prospects", 18th World Energy Congress, Buenos Aires, World Energy Council, London, Oct. 2001

[2] C. Sihler et al.,"Paralleling of two Large Flywheel Generators for the Optimisation of the ASDEX Upgrade Power Supply", Fusion Engineering and Design 58-59, Elsevier Science, 2001, pp. 41-45

[3] A. M. Miri, C. Sihler, "Damping of Resonances at Energization of Power Transformers in an Isolated Network", Conf. Proc. 38th Annual Meeting of IEEE Industry Applications Society, Salt Lake City, USA, 2003, in press

[4] P. Lang, T. S. Kulig, www.itwm.fhg.de (product: "torsional stress analyzer"), Germany, 1999

[5] C. Sihler et al., "Excitation of Torsional Oscillations in Generator Shafts by Plasma Feedback Control", Proc. 22nd SOFT, Fusion Engineering and Design, in press, www.sciencedirect.com, 2003

[6] C.-J. Wu, Y.-S. Lee, "Application of Simultaneous Active and Reactive Power Modulation of Supercond. Magnetic Energy Storage Unit to Damp Turbine-Generator Subsynchr. Oscillations", IEEE Trans. on Energy Conversions, Vol. 8, No. 1, 1993

[7] Simplorer, "Ref. Manual,Version 4.2", Chemnitz, Germany,2000

[8] S. Kulig, A. Joswig, C. Sihler, F. Stobbe, "Torsionsbeanspruchungen im Wellenstrang des Stoβkurzschluβgenerators EZ3 bei Plasmaexp"., IPP Internal Report, unpublished, July 2002

[9] A. Harada, "Dämpfung von subsynchronen Resonanzen mittels eines elektromagnetischen Regelkreises in einem Inselnetz", Master Thesis, University of Karlsruhe, unpublished, June 2003