Development of a stabilizer for oscillating torques in synchronous machines

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Abstract — **A novel torque stabilizer was developed and has been continously applied at IPP as a countermeasure to torsional vibration and resonance problems in synchronous machines. Such problems are most frequently encountered in rotor systems with long shafts and large inertias constituting a weakly damped mechanical resonator which exhibits a low resonance frequency, e. g. 10 – 30 Hz. The paper presents examples for the successful suppression of torsional resonances in synchronous machines of the IPP experimental power supply, an isolated power system based on flywheel generators. The novel torque stabilizer is a powerelectronic device which is connected to the stator winding of the synchronous machine. It produces the same effect as an increased natural damping for oscillation modes in the rotating shaft assembly. It is therefore universally applicable to torsional vibration problems in generators and electrical drive systems.**

Index Terms: Rotor dynamics, torsional vibration, subsynchronous resonance, power electronics, real-time control, numerical simulation

I. INTRODUCTION

The aim of nuclear fusion research is to develop a power plant deriving energy from the fusion of atomic nuclei. The fuel is an ionised low-density gas, a hydrogen plasma, which has to be confined in magnetic fields and heated to very high temperatures to ignite the fusion fire [1]. A tokamak is the most advanced type of magnetic plasma confinement device, with a high electric current of the order of Megaamperes flowing in the plasma. The IPP commissioned an experimental tokamak, called ASDEX Upgrade (AUG), in 1991. The principle design of this device is shown in Fig. 1. In order to magnetically confine the plasma, high DC currents (up to 70 kA) are necessary in the toroidal (1) and poloidal (2) magnetic field coils. The power supply for the magnet coils and additional plasma heating systems which are not shown in Fig. 1 requires an electrical power up to a few hundred MVA for several seconds. In order to exclude perturbations in the utility networks, the power supply of this experimental tokamak is based on flywheel generators.

A routine check of the flywheel generators powering the plasma experiments revealed damage to a coupling of the rotor shaft system of one generator. At first it could not be explained why traces of wear were observed on the coupling between a 76-ton flywheel and the synchronous generator driven by it. A thorough investigation revealed the cause: fast variation of the load on the generator from which different high electric energies are extracted in rapid succession during AUG plasma experiments can react on the complete system as an excitation and cause a torsional (subsynchronous) resonance in the rotor system [2]. The rotor of the generator then oscillates against the flywheel with a frequency below the network frequency. This was measured with a special torque sensor operating without contact which is described in section IV [3]. Although only minimal twisting by hundredths to tenths of a degree was found, the oscillating torque can get very high – values up to 5 MNm were measured. The alter-

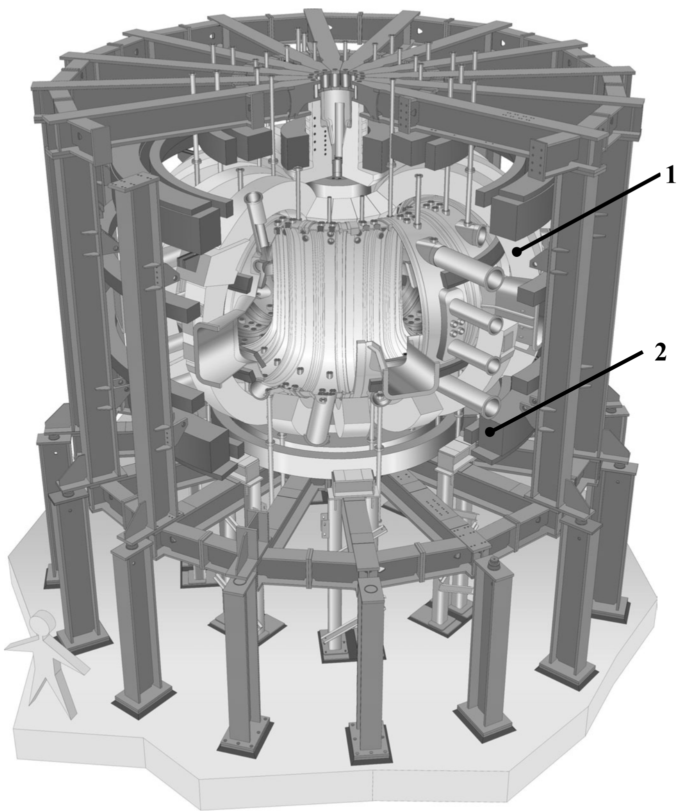

Figure 1. ASDEX Upgrade tokamak: The plasma is electromagnetically confined by D-shaped toroidal (1) and poloidal (2) magnetic field coils

nating stress caused by this torque incurs fatigue to the rotor shaft system which in the long term can lead to damage of couplings.

Once the generator was repaired, the plasma scientists resorted for the time being in terminating experiments whenever the measuring equipment indicated excessive torsional vibrations. In order to prevent negative effects on the durability of the shaft assemblies numerous plasma experiments had to be prematurely terminated by the generator protection system based on the torque measurements. Since the torsional resonance problems could not be solved by a control system based solution [2], a novel thyristor controlled device for stabilising the oscillating torques in the synchronous generators was developed.

II. CONCEPT OF THE TORQUE STABILIZER

Object of this development was to install one feedback controlled damping circuit (stabilizer) at each generator allowing to damp one mode of torsional resonance efficiently. Conventional methods applied in utility networks to damp subsynchronous resonance (SSR) phenomena [4] are either based on facilities providing a change of reactive power to increase torsional mode damping, e. g. thyristor controlled series capacitor, shunt reactor or SVC, or provide damping by modulating the output power by means of power electronic devices installed in the network, e. g. FACTS devices. Like these devices, the IPP torque stabilizers were designed to damp the mechanical resonance by means of active power. Object of using a separate stabilizer system was to influence the generator mechanical input without having to modify control parameters of the load (AUG) in order to exclude adverse effects on the performance of the plasma feedback control system, as explained in section III. The torque stabilizer is installed directly at the generator busbars (in parallel to the AUG load circuits) and operated independently from other control systems. In order to achieve this, the damping power is generated by a separate energy storage unit as described in section IV.

III. CHARACTERISTICS OF ASDEX UPGRADE LOAD CURVES AND IMPACT ON THE POWER SUPPLY

The power supply of the AUG tokamak consists of three distribution systems as shown in Fig. 2. Each is supplied by a dedicated flywheel generator: EZ2 which solely feeds the toroidal field coils, EZ3 (500 MJ / 144 MVA) and EZ4 (650 MJ / 220 MVA) which feed poloidal field coils and additional heating systems [5]. The design of these synchronous machines with a horizontal rotary axis and a big flywheel connected to the rotor shaft system is shown in Fig. 3.

The flywheel generators EZ3 and EZ4 are synchronous machines which are driven only by the flywheel during the plasma experiments. They supply networks in which high-power thyristor converters enable a fast control of the DC currents in the poloidal field magnet coils being used for magnetic confinement and stabilisation of the plasma. Normally, the power demand of a tokamak experiment can be characterised by a high active power (P) demand at the beginning of the plasma experiment when the magnetic field coils are energized and a feedback of active power (P < 0) at the end of the experiment when the magnetic field coils are de-energized by means of the thyristor converters and magnetic energy is fed back to the synchronous machines. If plasma instabilities occur, feedback control of the plasma-shape, -position and -current can cause fast changes in the load curve of the experiment leading to a dynamic reaction on the flywheel generators EZ3 and EZ4.

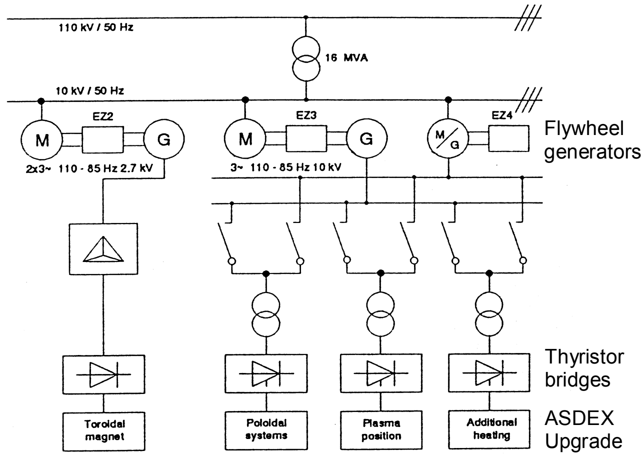

Figure 2. Structure of the IPP experimental power supply

Considering only fundamental components, the active power demand of a thyristor converter supplying a DC inductance can be approximated as follows:

$$P \approx U_{di\alpha}\ I_d = (U_{di0} \cos\alpha)\ I_d \qquad (1)$$

where

I_d DC output current;
U_{di0} converter no-load voltage;
α delay angle.

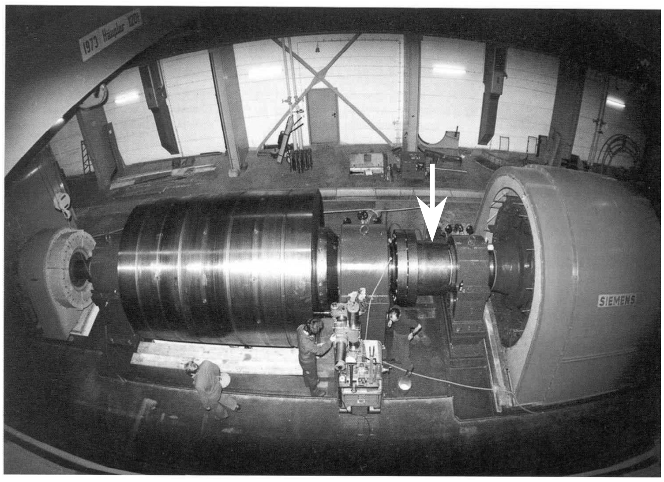

Figure 3. One of the flywheel generators at IPP: On the left the big flywheel; under the casing on the right the generator. The arrow shows where the sensor measures the torsional vibration of the axis.

In case of magnet coils with high inductance, the coil current I_d can be considered as approximately constant if voltage modulations with frequencies f > 20 Hz occur. I. e. for such frequencies the active power demand of a converter feeding an inductive load is directly proportional to the voltage modulation $U_{di\alpha}$. Considering, e. g., that the nominal short-time current and no-load voltage of the ohmic heating (OH) converter is I_{dN} = 40 kA and U_{di0} = 2.76 kV, equation (1) yields $P(t) \approx$ 110 MW $\cos\alpha(t)$. The OH converter is one of the converters being supplied by generator EZ4, as shown in Fig. 2.

Fig. 4 shows an example for these dependencies at the end of a plasma experiment performed with a plasma current of 800 kA. In case of plasma instabilities, recognizable in this example by means of oscillations appearing in the plasma current at t = 5.8 s, the plasma current controller causes a modulation of the current reference of the OH coil. Because of the large time constant of this coil, the modulation appears in the OH coil voltage.

Considering that these extreme active power oscillations act on single machines and that natural frequencies of 24 Hz and 26 Hz can be calculated for the shaft assemblies of the flywheel generators EZ3 and EZ4, such dynamic loads can cause a strong torsional resonance in the generator shafts. The lowest curve of Fig. 4 is the torque measured in the shaft assembly of the EZ4 generator during a resonant excitation. At this experiment a maximum torque of almost 5 MNm was measured before the experiment was terminated by the generator protection system. This load caused a torsional stress in the shaft similar to a static load with a magnitude higher than 700 MW. Due to the low natural (material) damping of the rotor system, even lower active power oscillations (with an amplitude of a few Megawatts) can cause torque values leading to damage in the shaft assembly.

During plasma experiments conducted in 2002, more than 100 electromechanical (subsynchronous) resonances measured on both flywheel generators of the poloidal field power supply were investigated by measurements and partly by numerical investigations. After a reduction of the trip levels of the generator protection system in order to exclude negative effects on the durability of the shaft assemblies, an unacceptable number of plasma experiments had to be prematurely terminated. A torque reduction by a factor of two could be achieved by a solution based on the plasma control system [2]. Since this solution adversely affected the performance of the fast plasma control [6], it was decided to develop a novel, effective method for damping oscillating torques without having to modify parameters of the flywheel generators or parameters of the AUG plasma control system.

IV. DEVELOPMENT OF THE DYNAMIC STABILZER FOR OSCILLATING TORQUES

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

$$\boldsymbol{J}\ddot{\boldsymbol{\phi}} + \boldsymbol{D}\dot{\boldsymbol{\phi}} + \boldsymbol{K}\boldsymbol{\phi} = \boldsymbol{B}\boldsymbol{u} \qquad (2)$$

where

$\boldsymbol{\phi}(t)$	torsion angles of the shaft;
$\boldsymbol{u}(t)$	externally applied torques;
$\boldsymbol{J}$	matrix of moments of inertia;
$\boldsymbol{D}$	damping matrix;

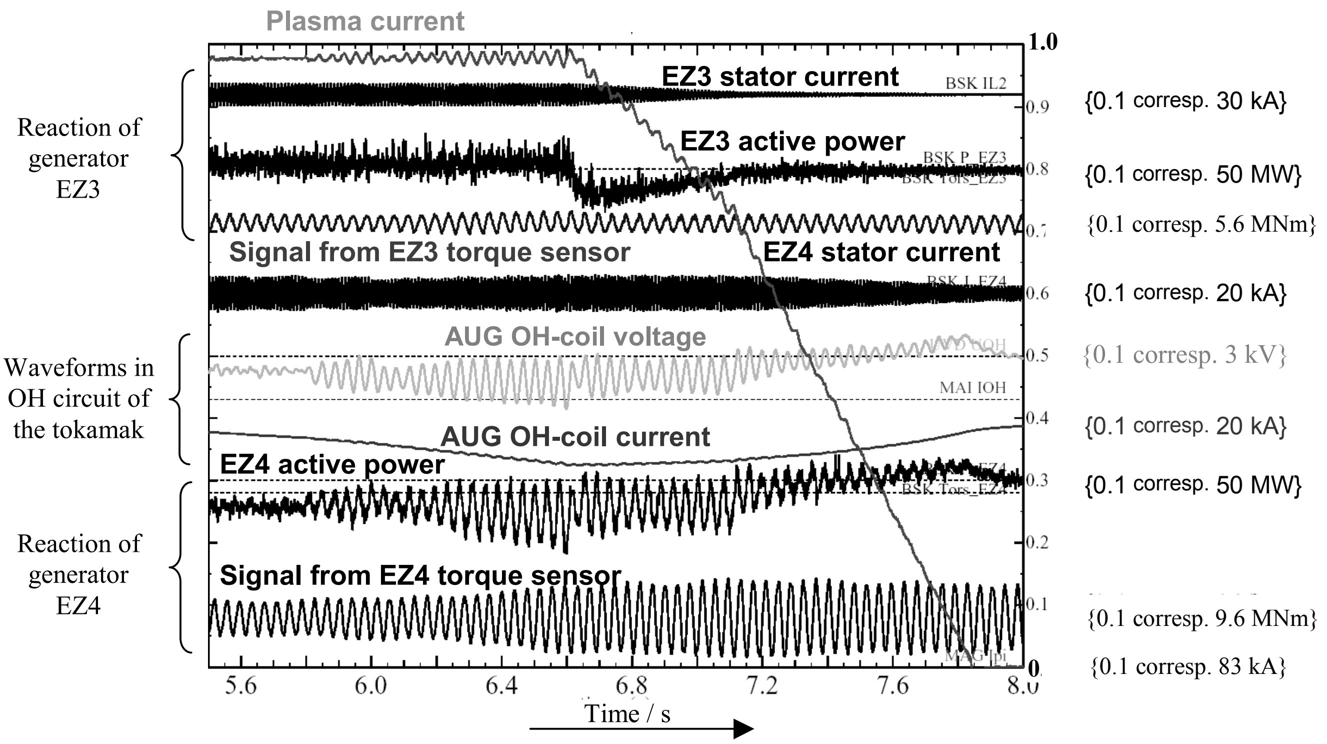

Figure 4. Impact of plasma current control on the flywheel generators EZ3 and EZ4: Measured oscillating torque in EZ4 shaft assembly

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 development of the torque stabilizer was based on applying an additional electromagnetic 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 electromagnetic torque in counter-phase to the torsional velocity of the shaft by means of the arrangement shown in Fig. 5. The torsional velocity is electronically derived from a torque sensor measurement in the block "Control System for Signal Modification". The mechanical torque measurement is performed with a sensor [3] especially suited for measurements on medium or large diameter shaft lines. The measuring concept is based on the anisotropic magnetostrictive effect in ferromagnetic materials. The permeability for the magnetisation in the direction of pressive stress is different in comparison with the direction of tensile stress. The sensor measures this difference, which is proportional to the mechanical torque in a range from 1 N/mm² - 1000 N/mm². The signal from the torque sensor can ideally be used in a feedback circuit because of the real-time characteristics of this measurement device. Fig. 5 shows the test set-up for a prototype dynamic stabilizer which was tested on flywheel generator EZ3. The "disturbance converter" in the test set-up is a 6-pulse thyristor converter in bridge connection feeding an inductor (AUG magnet coil) with an inductance of L = 34 mH. Purpose of the disturbance converter is to excite torsional resonances in the EZ3 shaft assembly similar as described in section III. The damping converter also is a current controlled 6-pulse thyristor bridge. Its current reference consists of a DC component (i_{trapez}) and an alternating component. The DC component is important because it enables to operate the inductor in the DC circuit as a buffer storage of magnetic energy, being loaded and unloaded in counter-phase to the torsional velocity of the shaft torsional oscillation which is represented by the signal i_{mod}. Since the torque stabilizer generates an electromagnetic torque acting on the rotor with a frequency corresponding to the resonant frequency, this damping method is very efficient

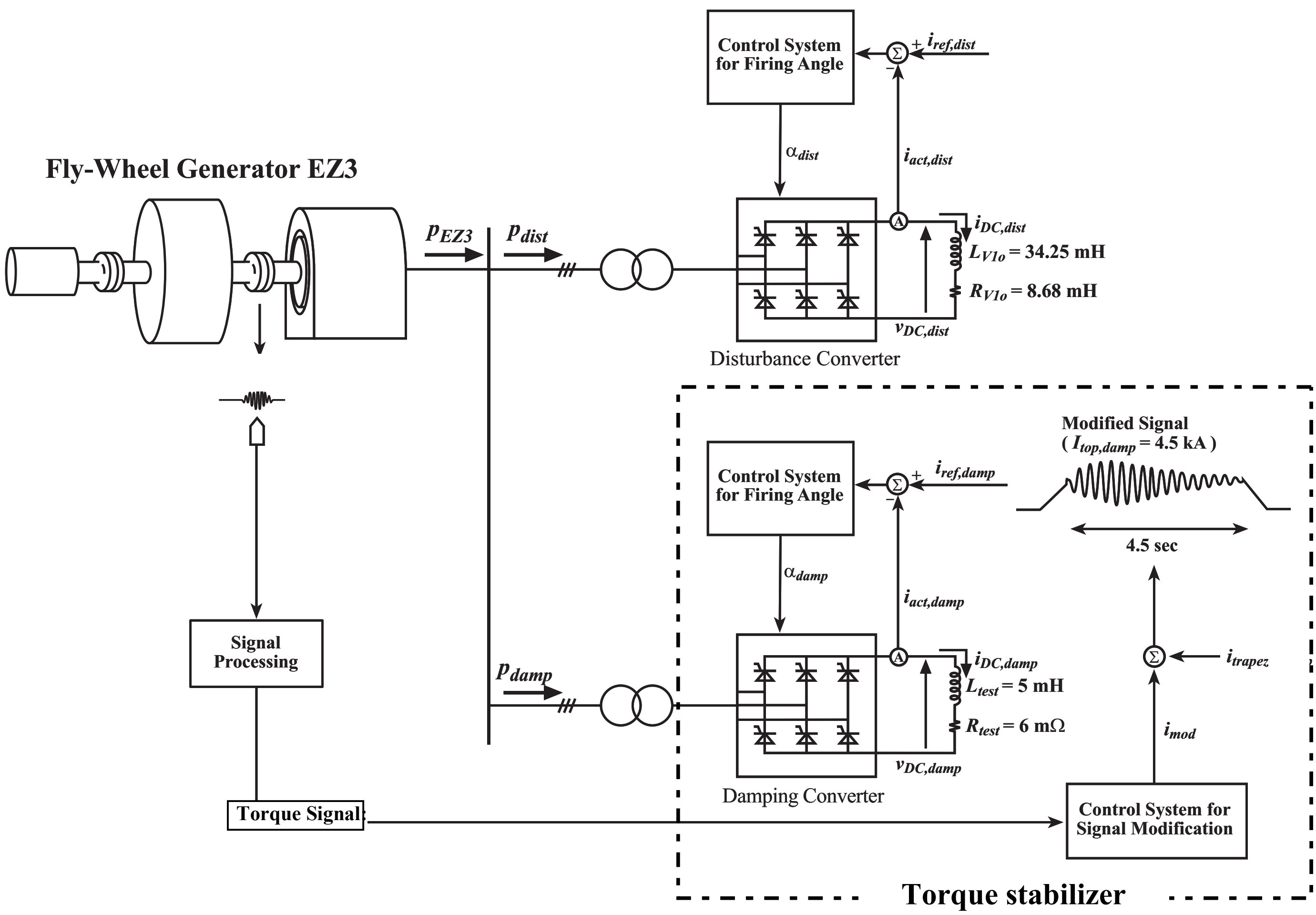

Figure 5. Schematic of test set-up for excitation (above: disturbance converter) and damping (below: torque stabilizer) of torsional oscillations in generator EZ3

For development and optimization of the torque stabilizer a numerical simulation model was derived using the program package Simplorer [7]. For such investigations a detailed model is required so that the non-linear properties of the synchronous machines, the dynamic loads (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 requires 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. 6) 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 in (2) in the general case. If the natural damping of the mechanical system is neglected, the differential equation system can be resolved with the additional variables given in equation (3):

$$
\begin{aligned}
\omega_{Mot} &= \frac{1}{J_{Mot}} \int (T_{Mot} - T_{MF})\, dt \\
\omega_{FW} &= \frac{1}{J_{FW}} \int (T_{MF} - T_{FG})\, dt \\
\omega_{Gen} &= \frac{1}{J_{Gen}} \int (-T_{el} + T_{FG})\, dt \\
T_{MF} &= K_{MF} \int (\omega_{Mot} - \omega_{FW})\, dt \\
T_{FG} &= K_{FG} \int (\omega_{FW} - \omega_{Gen})\, dt
\end{aligned}
\qquad (3)
$$

where

T_{MF} torque excerted at shaft between motor-rotor and flywheel;

T_{FG} torque excerted at shaft between flywheel and generator-rotor

The natural damping of the shaft was modelled on 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 the 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. Fig. 7 shows the control

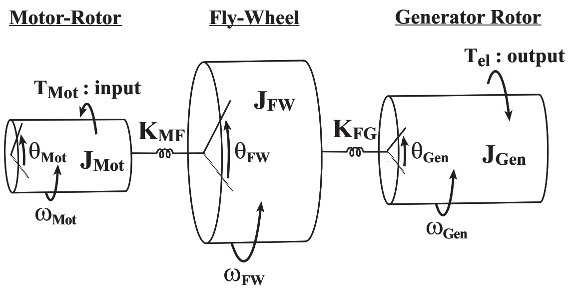

Figure 6. Mass-spring model of EZ3 shaft system

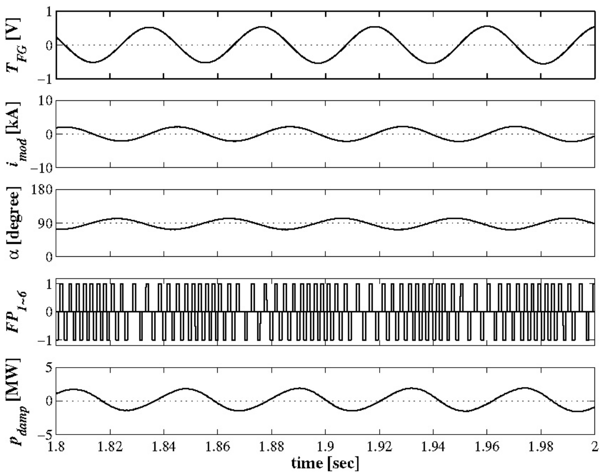

Figure 7. Numerical simulation: Control signals for damping power generation with the torque stabilizer shown in Fig. 6

signals and the power generated by the torque stabilizer in a numerical simulation which was performed accompanying the test program performed with a prototype stabilizer on generator EZ3. For testing and commissioning, the output power of the dynamically controlled torque stabilizer can be reduced in two ways:

- Electronically (reduced gain in the feedback loop)
- In the DC system allowing only a small DC current (static reference i_{trapez})

The latter is an important safety feature because tests can safely be performed at low power level of the stabilizer.

A water-cooled coil (L = 5 mH) was used as buffer storage of magnetic energy (load in stabilizer DC circuit) during the first tests performed with a prototype stabilizer circuit. An existing thyristor converter module of the ASDEX Upgrade power supply (U_{di0}= 1.5 kV, I_N = 22.5 kA) was used as "damping converter". During the tests, the DC currents were limited to low values by means of reference limiting and a trip level based on the thyristor converter current measurement. Additional protection was achieved by means of two (completely) redundant torque measurements with fast-acting trip-levels. After adjustment of the hardware in the feedback loop and optimum setting of all control parameters, the damping capability of the first active damping circuit could be demonstrated in tests as shown in Fig. 8. This test was performed with the configuration shown in Fig. 5. The disturbance converter was used to excite generator EZ3 (1st natural frequency: 24 Hz) to torsional resonance at 1s < t < 2s. At t = 2 s the torque stabilizer was activited in ramping up the DC current (i_{trapez}) to a value of 5 kA. In this test not the 5 mH inductor shown in Fig. 5 but a 1 mH inductor was used acting as buffer storage of magnetic energy in the stabilizer.

Parametrical studies performed with the numerical simulation model show that the effectiveness of using feedback controlled buffer storage of magnetic energy is not limited to low values of the inductor or converter output power. The diagram in Fig. 9 shows that a maximum torque of 1.2 MNm (actual setting of trip level of EZ3 generator protection)

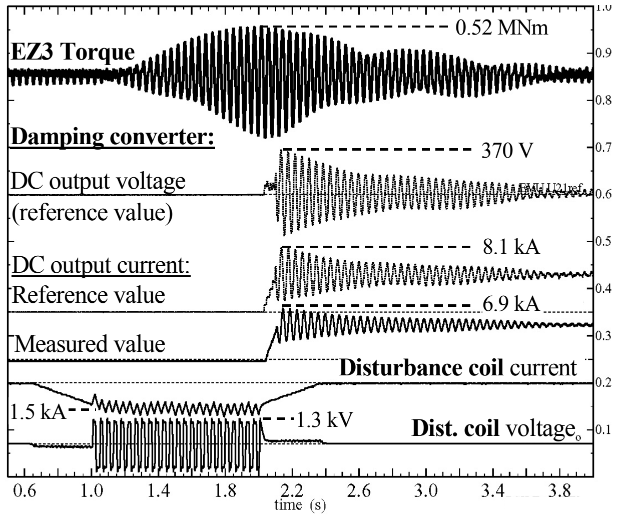

Figure 8. Resonance excitation of flywheel generator EZ3 and test of a prototype dynamic torque stabilizer (inductor with 1 mH)

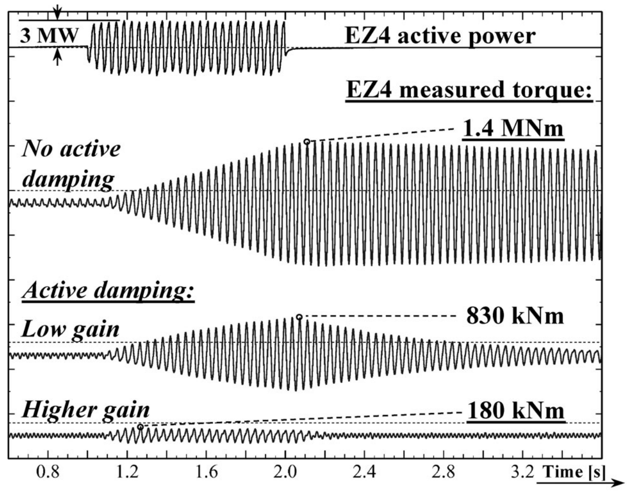

Figure 10. Resonance excitation of flywheel generator EZ4 and test of a dynamic torque stabilizer based on a 5 mH-inductor (at low and high operational gain in the feedback controlled stabilizer circuit)

is not exceeded as long as the resonant disturbance power stays below 4.5 MW (using a damping converter with a no-load voltage of 500 V) respectively 14.5 MW if a 1.6 kV damping converter is used. Fig. 10 shows measurement results achieved during tests performed with generator EZ4 (1st natural frequency: 26 Hz). If the feedback controlled stabilizer is operated at high operational gain, torsional vibrations can be almost totally suppressed (lowest curve in Fig. 10). After successful completion of the numerical investigations and tests two stabilizers were permanently installed in the AUG power supply: A stabilizer with a 1 mH inductor in the three-phase system of generator EZ3 and one with a 5 mH inductor on generator EZ4. The stabilizer circuits are operated at moderate operational gain during all plasma experiments.

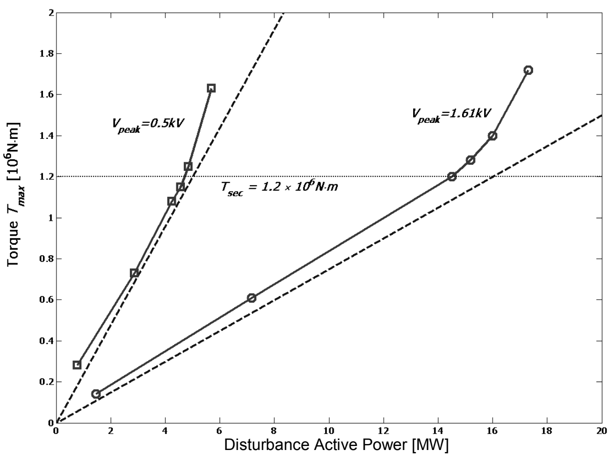

Figure 9. Result of parametrical study performed with torque stabilizer (5 mH inductor) operated with a DC current of 10 kA

V. Operational Experience with the Torque Stabilizers Installed at IPP

Since installation and commissioning of the torque stabilizers they have been continuously used during plasma discharges. Up to now (February 2004) the effectiveness and robustness of this electromagnetic damping method has been proven in more than 1500 plasma experiments, partly causing extreme reactions on the flywheel generator power supply. Examples for damping electromechanical resonances are shown in Figs. 11 and 12. Fig. 11 shows resonance damping at generator EZ4 after the occurrence of active power transients with a peak-to-peak value of 114 MW. They were caused by a not optimized scenario for ramping up the plasma current.

A more typical result from ASDEX Upgrade operation is shown in Figs. 12 (a) and (b). These curves were measured during the plasma experiments # 16971 and # 17779 causing comparable load curves. 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. 12 (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. 12 (b) active damping was provided by means of a torque stabilizer 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. In using a DC current of 5 kA flowing in the 1 mH-inductor of the EZ3 stablizer, the magnetic energy stored in the inductor is only in the order of tens of Kilojoule. However, the stabilizer provides sufficient damping power for this torsional resonance

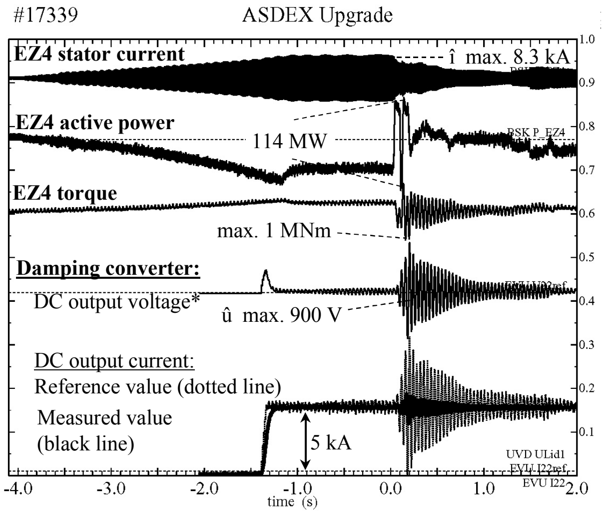

Figure 11 (a) Stabilization of oscillating torque caused in generator EZ4 by extreme active power transients

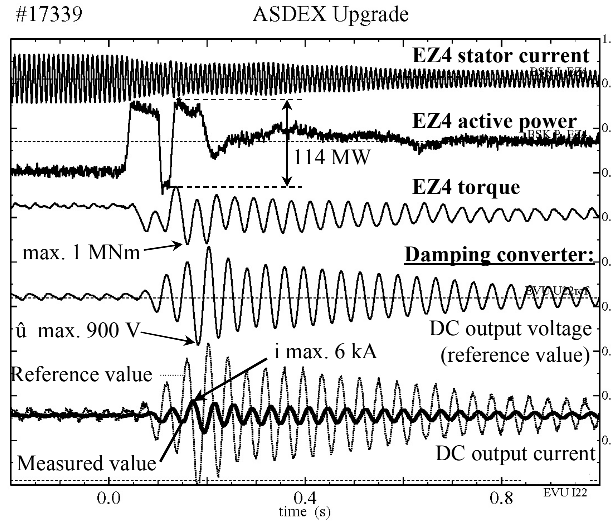

Figure 11 (b) Deatil of Fig. 11 (a)

phenomenon in a shaft assembly weighing more than 100 tons. Main reason for this is the high Q-factor of the first torsional mode of the shaft assembly and the fact that the stabilizer generates a damping power corresponding to the resonant frequency of this mode.

The damping power of the IPP torque stabilizers has been limited to values below 10 MW because that provides sufficient damping for the experiments performed on ASDEX Upgrade. This can be shown by the diagram in Fig. 13 which was derived from a statistical evaluation of measurement results from 1400 plasma experiments. The torque stabilizer was only activated during feedback controlled plasma experiments. During feedforward controlled experiments the torque stabilizer was not activitated ($P_{max} = 0$ in Fig. 13) because the torsional vibrations in the synchronous machines are negligible (no excitation of oscillating torques).

While the torque stablizer was activitated, the torque trip level of the generator protection system was not reached which can be explained by the proportional characteristic of the stabilizer controller.

VI. CONCLUSION

Two novel thyristor controlled devices for stabilizing oscillating torques in synchronous machines have been developed, installed, tested and continously operated in the pulsed

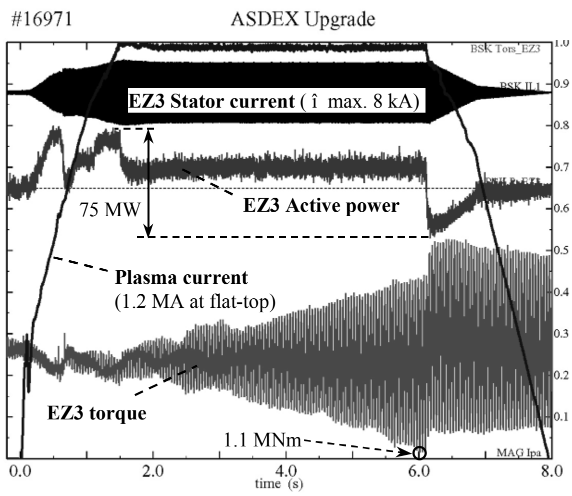

Figure 12 (a) Measured EZ3 generator current, active power and torque showing a torsional resonance excited by active power transients during AUG plasma experiment # 16971

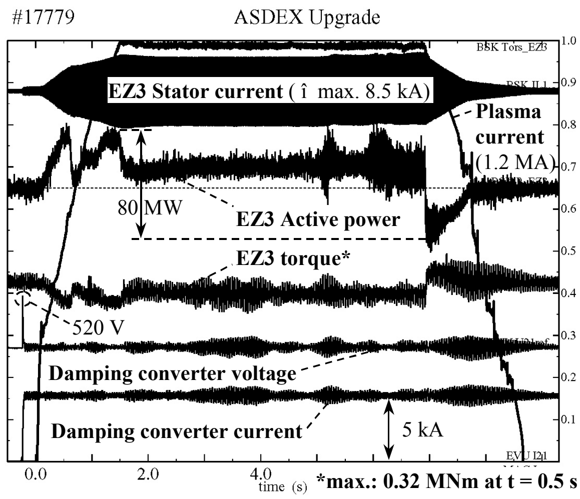

Figure 12 (b) Stabilization of the oscillating torque caused by a plasma experiment comparable to # 16971 in using the EZ3 torque stabilizer at low operational gain (damping power < 1 MW)

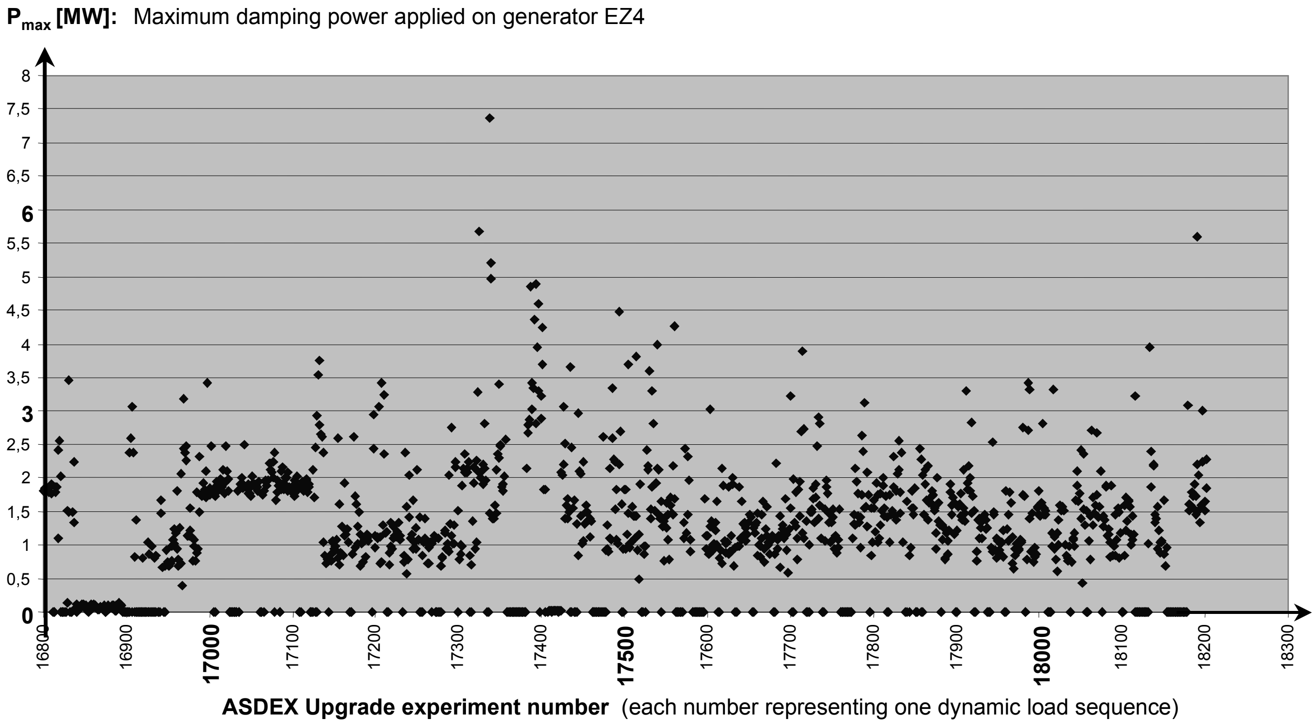

Figure 13. Measured maximum damping power provided by the EZ4 torque stabilizer in 1400 dynamic load sequences

power supply of a tokamak experiment. In parametrical studies performed with a detailed numerical model and experimentally in more than 1000 dynamic load sequences the novel torque stabilizer has proven to be a stable, efficient, and reliable method of damping oscillating torques in synchronous machines. Connected to the stator winding the stabilizer produces the same effect as an increased natural damping for oscillation modes in the rotating shaft assembly. Therefore, it can not only be applied to problems with oscillating torques in power systems but also to electrical drive systems. The nominal power of the torque stabilizer can be 10 – 100 times smaller than the nominal power of the synchronous machine. This allows a cost-effective design. Since the stabilizer can simply be installed, studies on applying this method to subsynchronous resonance damping in turbo-generators (using the IEEE First Benchmark Model on SSR [10]) and on stabilizing oscillating torques in the rotor shaft system of electrical drives are presently performed. The simulations show that the active damping method presented in this paper can also be applied for damping more than one torsional mode of oscillation in multi-mass systems.

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