Reduction of Harmonic Distortions and Subsynchronous Resonances in the Pulsed Power Supply of a Nuclear Fusion Experiment

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Abstract – **The ring-shaped hydrogen plasma of ASDEX Upgrade (AUG), an experimental tokamak for nuclear fusion research, carries an electric current up to 1.4 MA. The generation and magnetic confinement of the plasma current requires an electric power of several hundred MVA for short time periods (up to 10 s). To keep away the pulsed load from the public utility grid, the power and energy is provided by separate networks based on flywheel generators. Voltage distortions measured on the 10.5 kV busbars were increased by resonances caused by the subtransient reactance of one generator and the stray capacitance of the transmission cables. The shape of the busbar voltages could be significantly improved by a simple modification of existing static var compensators. The dynamic load curves of feedback controlled fusion experiments feature frequencies which are in the same range as the first eigenfrequency of the flywheel generator shaft lines (about 25 Hz). In order to protect the generators from subsynchronous resonances (SSR) torque sensors were installed. The paper presents simulated and measured results and describe the measures taken to achieve a significant reduction of torsional stresses in the generator shaft lines.**

Keywords – separate network, thyristor converter, harmonic, flywheel generator, shaft line, subsynchronous resonance, SSR

I. INTRODUCTION

For more than three decades, world-wide efforts have been made to investigate the fusion of the hydrogen isotopes deuterium and tritium for energy production. A number of principles are available for the experimental devices serving this purpose. One of the most favorable is the toroidal confinement of an ionized gas (plasma) which is heated to about 100 million degrees and confined in a vacuum chamber by the field of large magnet coils. The type of magnetic plasma confinement device, with a high electric current of the order of several Megaamperes flowing in the plasma, is named tokamak. The performance of a tokamak discharge can be significantly improved by optimising the shape of the plasma column. An elongated D-shaped cross-section is needed for optimal confinement. Position control is required because of the immanent vertical instability of elongated plasmas. Shape control is necessary to accurately establish and maintain the optimized profile.

The Max-Planck-Institut für Plasmaphysik, Garching, commissioned an experimental tokamak, called ASDEX Upgrade (AUG), in 1991. The plasma shape of the AUG tokamak is determined by the poloidal field (PF) magnet coils. Stabilization of the vertical plasma position is performed by means of two inner control coils. Six vertical field-coils in a reactor-relevant configuration are the main plasma shaping coils. The ohmic heating coils (OH) induce the plasma current. The currents in these coils are feedback controlled [1]. Multivariable control is considered mandatory, because of the strong cross-couplings in the system.

The power supply of the AUG tokamak consists of three distribution systems (110-85Hz) as shown in Fig. 1, each 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 vertical field coils and additional heating systems. Normally, the power demand of a tokamak experiment can be characterised by a high active power demand (P > 0) during plasma ramp-up, a relative small demand of P during the plasma flat-top phase and a feedback of active power (P < 0) during plasma ramp-down, as shown in Fig. 2.

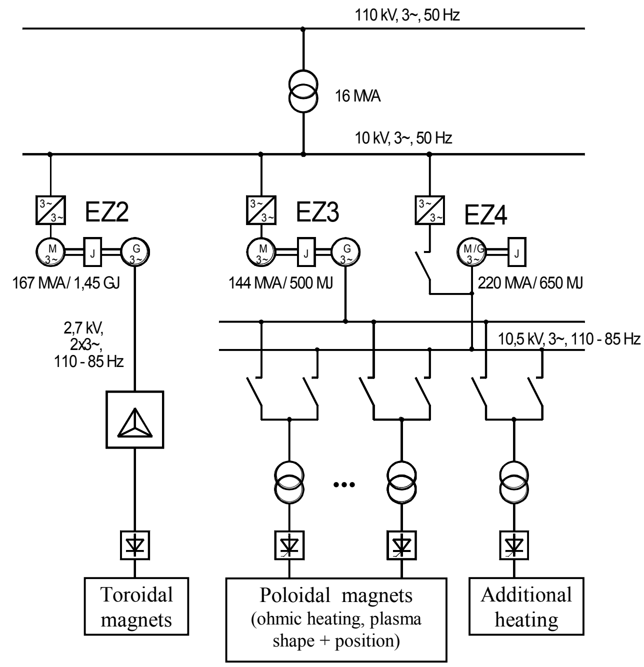

Fig. 1: Structure of ASDEX Upgrade power supply

Plasma feedback control can cause fast changes of the P demand in the power supply, especially in the EZ3 and EZ4 networks where thyristor converters are supplied allowing fast control of the DC currents in the magnet coils used for plasma position and shape control. As an example, Fig. 2 shows the current and voltage of a PF magnet coil during a 1 MA plasma discharge, together with relevant time histories measured in the EZ3 power supply.

II. IMPACT OF PLASMA EXPERIMENTS ON THE POWER SYSTEM

The plasma experiments conducted at IPP cause mainly two kinds of harmonics: Higher frequency (kHz-range) and lower frequency (subsynchronous) harmonics. The lower frequency harmonics are dealt with in section III.

A. AUG load curves and impact on the busbar voltages

The large inductive voltage required by the poloidal field coils of a tokamak during current ramp-up and plasma ignition leads to a large reactive power demand from the thyristor converters during the plasma flat-top phase, as the firing angles are phased-back. Typically, the load power factor drops from 0.6-0.8 during the plasma current rise to 0.2-0.3 during the plasma current flat-top phase. The plasma current flat-top phase, in which the physical experiments are conducted, is characterized by a phase delay angle α of $\alpha \approx \pi/2$. Two methods for improving the power factor are applied in the AUG power supply, namely the control of the phase-to-neutral voltage in thyristor converters fitted with neutral thyristors, such as a new 145 MVA modular thyristor converter system [2], and reactive power control achieved by means of a 120 MVAr static var compensation system [3].

During the plasma current flat-top phase, high frequency oscillations (about 10 kHz), as shown in Fig. 3 in an extreme case, could be measured in the EZ3 network. Under these conditions several AUG plasma discharges requiring an apparent power of 100 MVA (or above) from EZ3 were interrupted due to converter malfunctions in the EZ3 network.

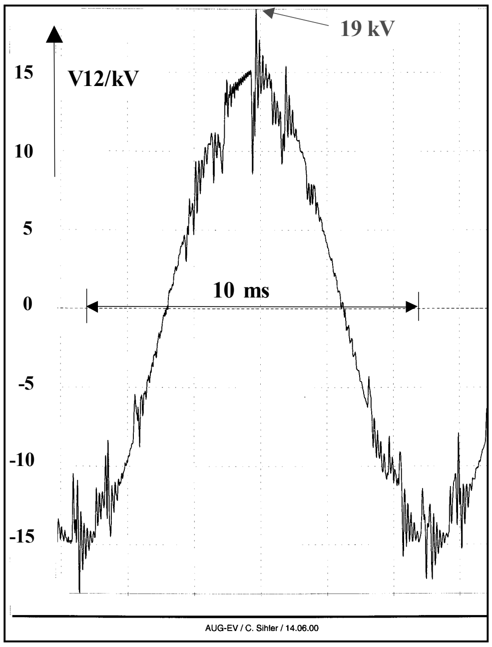

Fig. 3. Measured distortion of the EZ3 busbar voltage during the plasma current flat-top phase (AUG # 13794, 1 MA)

B. Counteracting measures

In order to clarify the cause of the 10 kHz oscillations and to derive efficient counteracting measures the simulation model shown in Fig. 4 was developed using the Simplorer code [4]. The following parameters of the separate network fed by flywheel generator EZ3 were used in the model: Subtransient reactance of EZ3: 230 µH, earth capacitance of three-core cable (10 kV, area of conductor 120-150 mm^2), 0.35µF/km, 10 cables in parallel with a length of 300 m each result in a total cable earth capacitance of about 1 µF. With these parameters a resonant frequency of 10 kHz can easily be calculated.

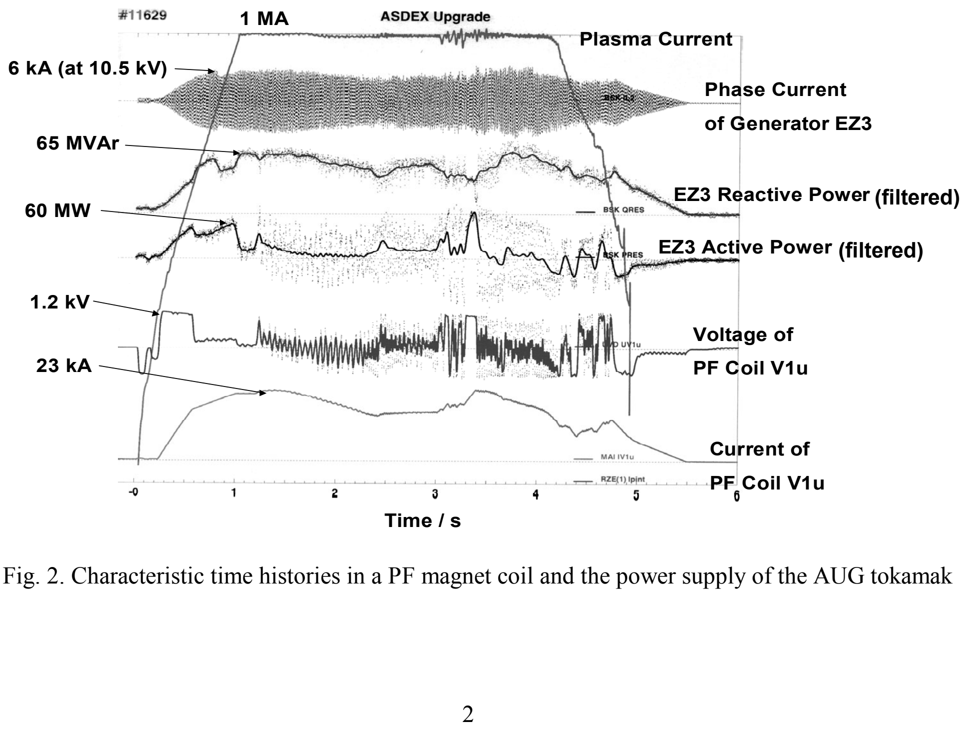

Fig. 2. Characteristic time histories in a PF magnet coil and the power supply of the AUG tokamak

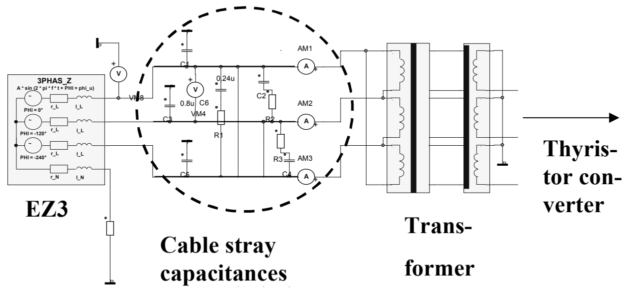

Fig. 4. Simulation model used for numerical investigations

To find an efficient way to suppress the 10 kHz oscillations which endangered the performance of all converters connected to the EZ3 network, numerical simulations were performed. In the simulations only one converter (6-pulse) was connected to the EZ3 network. Typical parameters were used for the load (magnet coil), high current converter and converter transformer [5]. A typical simulation result considering the cable stray capacitances is shown in Fig. 5.

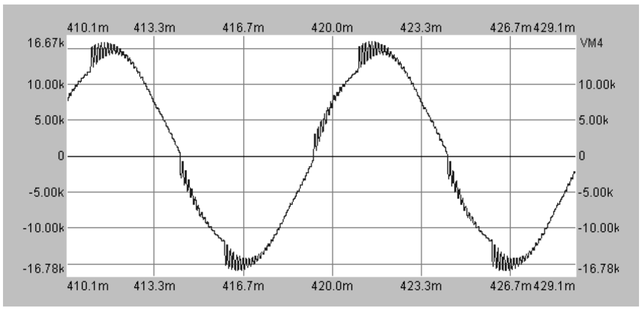

Fig. 5. Simulated busbar voltage considering one 6-pulse thyristor converter fed by the 3-phase system shown in Fig. 4

Considering that there are several converters with different characteristics and loads connected to the EZ3 busbars, the highly distorted busbar voltages could be explained by resonances due to the cable stray capacitances and the subtransient reactance of EZ3. One object of the simulations was to investigate the influence of the SVC (static var compensation) modules on the measured high frequency oscillations (10 kHz) and to clarify whether the high frequency oscillations in the EZ3 network can be suppressed in modifying the design of the SVC modules as shown in Fig. 6. Additinal damping resistances were installed in parallel to the inductors (encircled in Fig. 6 with dotted lines). The original design of the SVC modules did not affect the 10 kHz oscillations since it consisted of 2.7 mH inductors in series with the SVC capacitors (with 67.2 µF).

After this modification each SVC module acts as a filter in providing a damped bypass for high frequency oscillations between the phases of EZ3. These resistances provide sufficient damping for 10 kHz oscillations, even if only one SVC module is connected (which is always the case during high power pulses). Figs. 7.a and 7.b show the quantitative effect of the modified SVC modules on the EZ3 busbar voltage.

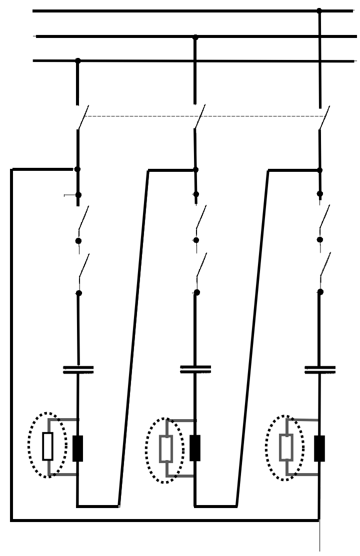

Fig. 6. Enhancing the design of existing reactive power compensation modules by means of additional damping resistances

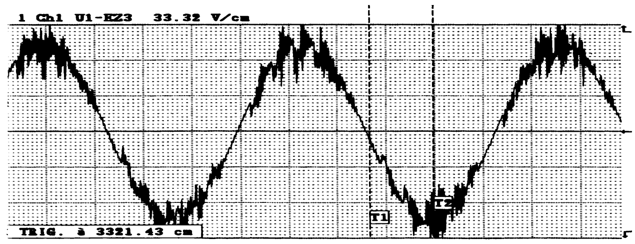

Fig. 7.a. Busbar voltage in EZ3 network during 1 MA plasma current flat-top phase (no SVC modules connected)

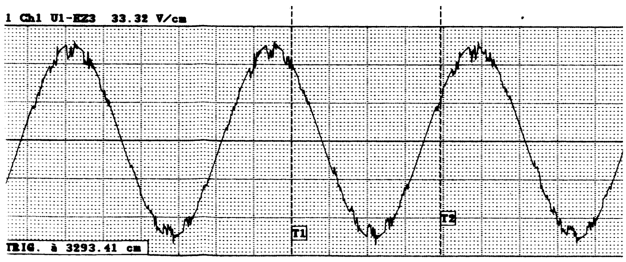

Fig. 7.b. Same plasma discharge as in Fig. 7.a, but four enhanced SVC modules connected

III. EXCITATION OF SUBSYNCHRONOUS RESONANCES BY PLASMA FEEDBACK CONTROL

A. Excitation of Torsional Oscillations in Generator Shaft Lines by Plasma Feedback Control

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

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

I_d: DC output current, U_{di0}: Converter no-load voltage, α: delay angle

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 higher frequencies the active power demand of a converter feeding a large coil is directly proportional to the voltage modulation $U_{di\alpha}$. Considering the nominal values in pulsed duty I_{dN} = 40 kA and U_{di0} = 2.76 kV of the AUG ohmic heating (OH) converter, equation (1) yields P(t) ≈ 110 MW cosα(t). Fig. 8 shows an example for these dependencies at the end of the plasma current flat-top phase of a 800 kA plasma discharge (AUG #15584) . In case of instabilities, e. g., in the plasma current, the plasma current controller causes a modulation of the ohmic heating (OH) coil current reference. Because of the large time constant of the OH coil, this modulation appears in the OH voltage. The corresponding active power oscillations with high amplitude act on single machines (EZ3 respectively EZ4). Considering that natural frequencies of 23.6 Hz respectively 26 Hz can be calculated for the shaft lines of the flywheel generators EZ3 respectively EZ4, torque measurement systems suited for a reliable monitoring of the torsional stress in the shaft lines of both machines were installed [6].

B. Investigation of torsional stress by simulation and measurement

Novel torque sensors have been developed for contactless measurement of mechanical torque by the University of Dortmund (Prof. Kulig) and ITWM (Fraunhofer Institut für Techno- und Wirtschaftsmathematik) [7]. Their main fields of applications are medium and large diameter shaft lines, especially if no other measurement technique can be used efficiently. The measuring concept is based on the anisotropic magnetostrictive effect in ferromagnetic materials. The sensor signal is directly proportional to the torsion of the shaft line.

A dynamic measurement is stringent at dynamic load curves as shown in Fig. 2 since generator shaft lines can be excited to torsional oscillations as described by the following n-dimensional differential equation system:

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

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

The novel torque sensors were installed close to the coupling between the flywheel and the rotor (as indicated by an arrow in Fig. 9). A measurement result typical for the

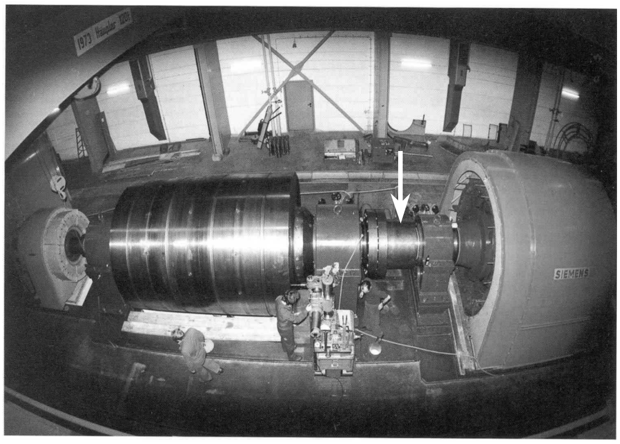

Fig. 9. Location of the torque sensor (the photo shows the EZ2 shaft line which has different parameters but a similar design)

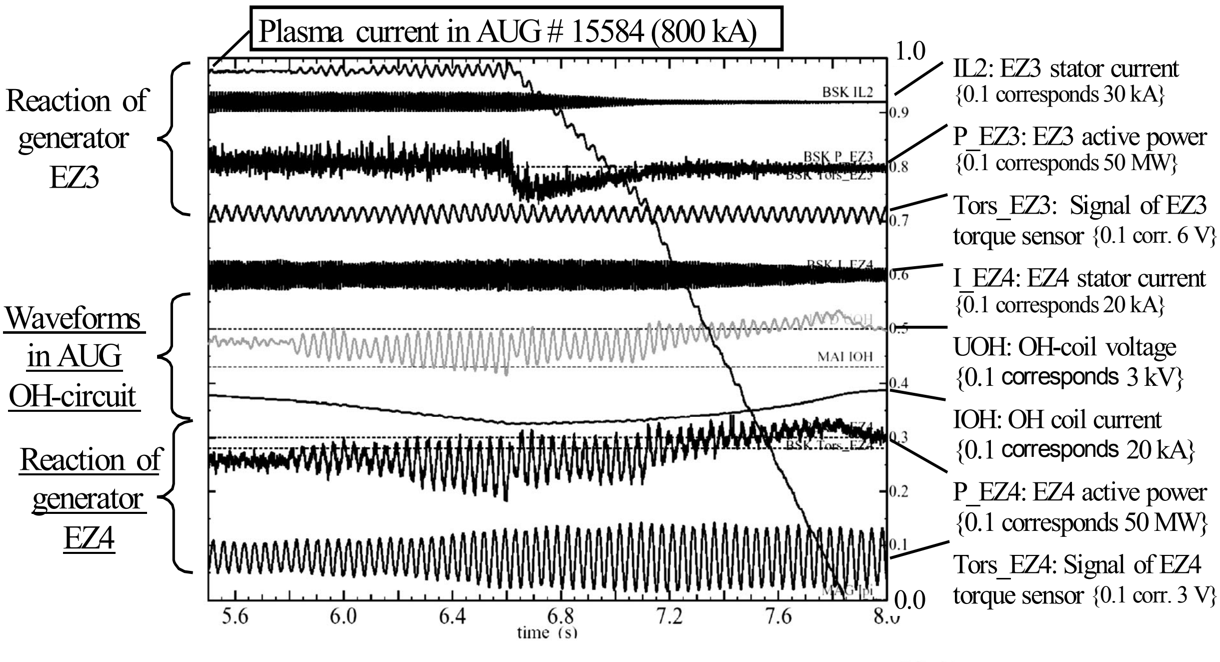

Fig. 8. Impact of plasma current control on EZ4 network (feeding OH converter and others)

resonant excitation of the EZ4 shaft line is shown in Fig. 8 (lowest curve). During AUG plasma pulse # 15584 the amplitude of the EZ4 torque signal exceeded 1.5 V. The sensor was calibrated with $3.2 \cdot 10^6$ Nm/V resp. 500 MW/V (at 100 Hz), i.e. the measured signal corresponds to an electrical power of 750 MW (applied under static conditions). Fig. 10 shows the excitation of torsional oscillations on generator EZ4 during the plasma current ramp-up phase (t = 4.35 s: Ignition of the plasma). The active power oscillation right after ignition of the plasma has a frequency of 26 Hz (1st eigenfrequency of the shaft line which leads to torsional oscillations with amplitudes corresponding to torques of $2 \cdot 10^6$ Nm.

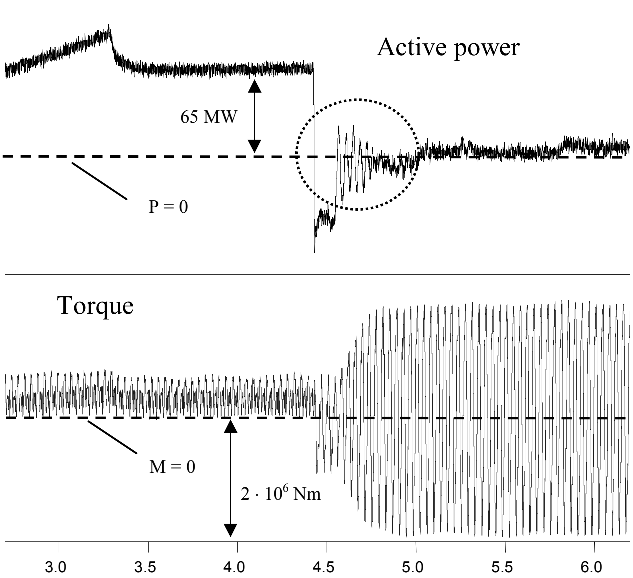

Fig.10. Active power oscillations measured on generator EZ4 during the plasma current ramp-up phase

The dynamic response of the shaft line can be understood in looking at the calculated resonance curve of a shaft line of similar design which is displayed in Fig. 11 [8].

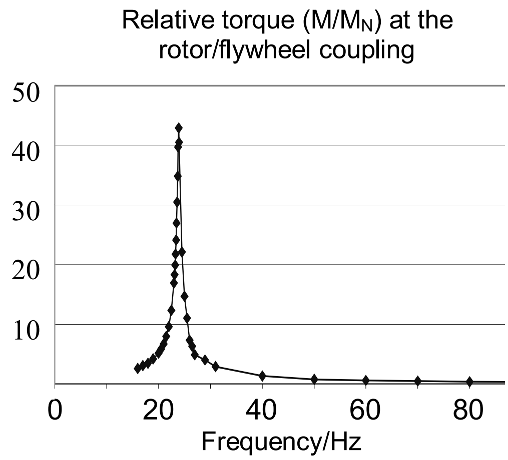

Fig. 11. Calculated resonance characteristic of EZ3 shaft line

C. Counteracting measures

Torsional oscillations due to resonance excitation (subsynchronous resonances) were also measured on the shaft line of flywheel generator EZ3. As a consequence of these measurement results the sensor signals are monitored during each plasma pulse and a trip level was set causing an early termination of the pulse if a predefined value is exceeded.

Since SSR phenomena could be observed during many plasma pulses of the 2001/2002 experimental campaign, it was decided to lower the trip settings for torsional stress in the shaft lines of EZ3 and EZ4 to 66 % of the values occuring in extreme cases (see Fig. 8) in order to exclude negative effects on the durability of the shaft lines. To avoid early terminations of plasma experiments by that protection, a *Butterworth* filter (4th order, corner frequency: 20 Hz) was applied to the current reference of the OH converter. By installation of the filter and new optimization of the plasma current controller, a reduction of torsional stresses in the shaft lines of both generators by a factor of 2 could be achieved. Fig. 12 shows the measured torques during two comparable plasma shots AUG #15865 (without filter) and AUG #15904 (with filter).

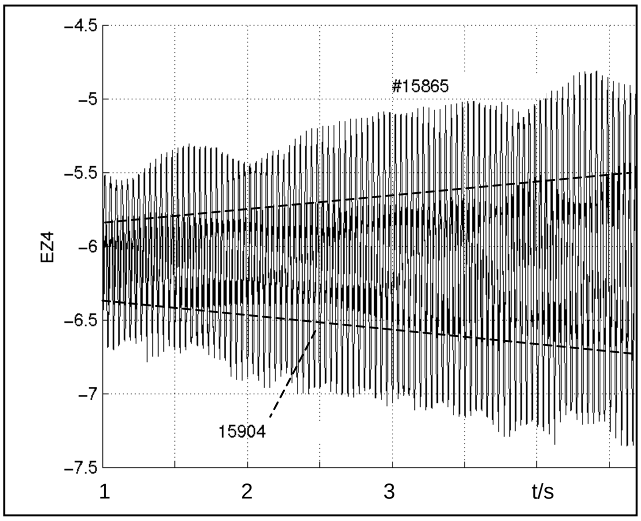

Fig. 12. Example for the reduction of torsional amplitudes on generator EZ4 by *Butterworth* filtering

The *Butterworth* filter adversely affects the dynamic behaviour of the plasma current control since it causes a phase shift in the control loop starting at frequencies below 10 Hz. To overcome this problem, a specially adapted *Bessel* filter was developed and will be tested in the next experimental campaign. To exclude damages to the couplings of the flywheel generator shafts, the trip levels will be further reduced by the end of 2002. Since this would cause an early termination of a not acceptable number of plasma experiments, a further reduction of torsional oscillations by electromagnetic damping is under investigation. The basic design is shown in Fig. 13.

The output of the torque sensor will be filtered, superposed to a static value (offset) and used as reference for a conver-

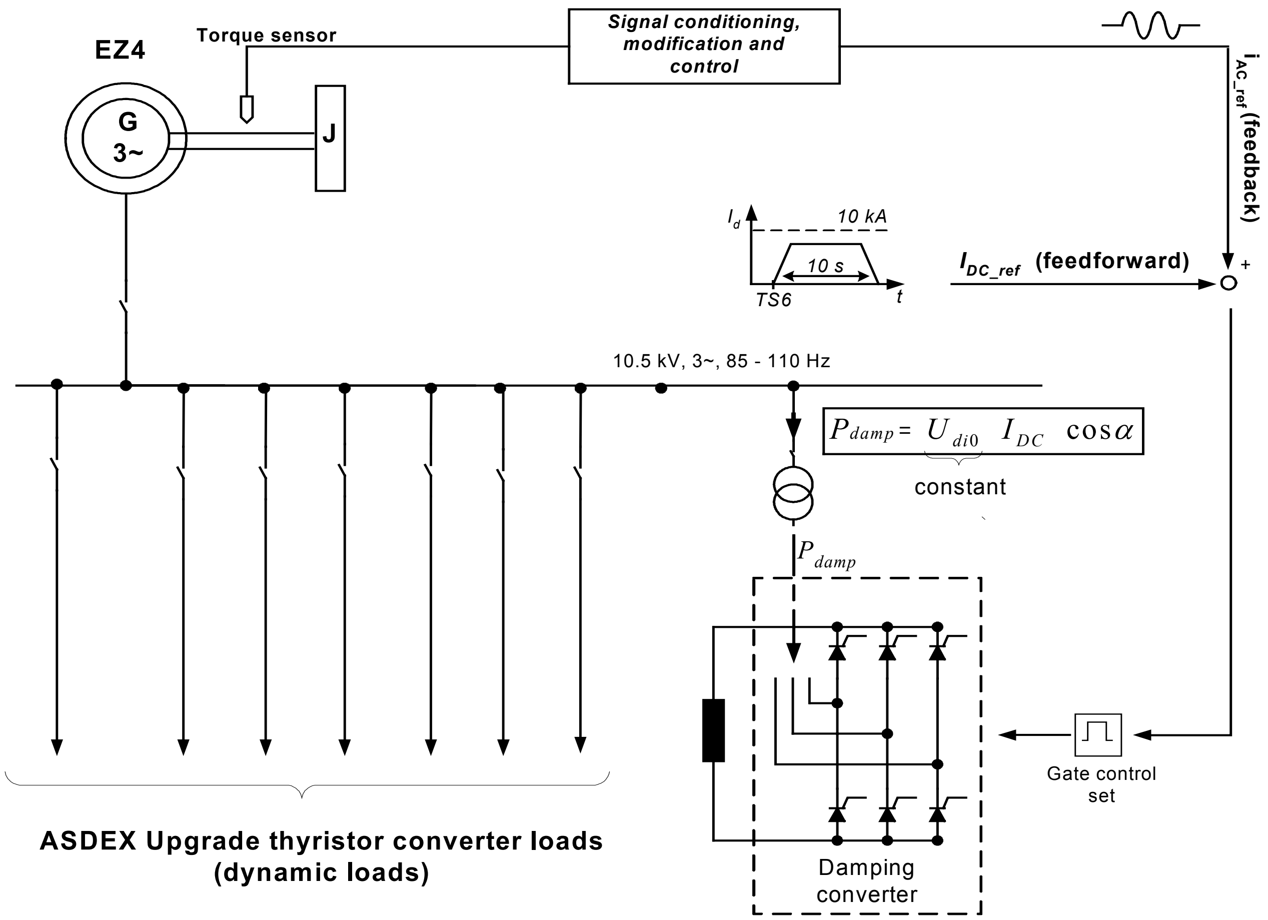

Fig. 13. Basic design of feedback loop for electromagnetic damping of subsynchronous resonances

ter feeding a test coil (magnet separate from AUG experiment). If subsynchronous resonances occur, the measured oscillation will be phae shifted and used as input of the 'damping converter'. The damping converter will produce an oscillating load curve with a phase shift of about 180° compared to the velocity of the torsional oscillation. Since it will be operated at the measured eigenfrequency of the shaft, only little power is necessary to damp these oscillations (see Fig. 11). The power of the 'damping converter' will be limited to low values, for safety reasons. Protection systems will ensure a safe operation of the damping converter. First tests will start in January 2003.

IV. CONCLUSIONS

During plasma experiments performed with experimental tokamaks a high degree of harmonic distortions can occur in the separate networks of the pulsed power supply. Distortions measured on the 10.5 kV busbars of the ASDEX Upgrade power supply were increased by resonances. Investigations performed by simulation and measurement show that the power quality in the pulsed network could be significantly improved by a simple modification of existing static var compensators (SVC).

Plasma feedback control can cause subsynchronous resonances in the shaft lines of the flywheel generators feeding the experiments. Therefore, devices capable to measure the torsional stress in the shaft line are stringent for generator protection. The mechanical stresses in the shafts could be reduced by a factor of 2 in applying a *Butterworth* filter to the plasma current control loop. Further progress shall be achieved by means of a separate thyristor converter providing electromagnetic damping in case of SSR excitation.

REFERENCES

[1] W. Treutterer et al., *Plasma Shape Control Design in ASDEX Upgrade*, Proceedings of 19th Symposium on Fusion Technology, Lisbon, Portugal (1996), pp. 933-936

[2] C.-P. Käsemann et al., *145 MVA Modular Thyristor Converter System with Neutral Control for ASDEX Upgrade*, Proc. 22nd SOFT, Fusion Engineering and Design, Elevier Science, 2003.

[3] C. Sihler, M. Huart, B. Streibl, D. Hrabal, H. Schmitt, *Transient Performance of Vacuum-Switched Static VAR Compensators Optimised for Large Induct. Loads*, Proc. IPST 2001, Brazil, pp. 481-486

[4] SIMEC, *Simplorer*, Version 4.2, Chemnitz, Germany, 2000

[5] A. M. Miri, *"Ausgleichsvorgänge in Elektroenergiesystemen"*, Springer Verlag, ISBN 3-540-67735-6, 2000

[6] C. Sihler et al., *Excitation of Torsional Oscillations in Generator Shaft Lines by Plasma Feedback Control,* Proc. 22nd SOFT, Fusion Engineering and Design, Elevier Science, 2003.

[7] P. Lang, T. S. Kulig, *http://www.itwm.fhg.de/as/projects/torsion/torsion_dt.html*, 1999

[8] T. S. Kulig et al., *Torsionsbeanspruchungen im Wellenstrang des Stoßkurzschlußgenerators EZ3 bei Plasmaexperimenten*, IPP Internal Report, unpublished, Juli 2002