Power Electronic Devices for Damping Torsional Vibrations

A. M. Miri, T. Zöller, T. Leibfried

Abstract—**Torsional vibrations and resonance problems with synchronous machines 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. It is impossible to obtain a effective mechanical damping for these torsional vibrations, but by using a power electronics device and an inductive or capacitive energy storage which is connected to the stator winding of the synchronous machine, which produce the same effect as an increased natural damping for oscillation mode in the rotating shaft assembly. This electrical method is applicable to torsional vibration problems in generators and electrical drive systems. The paper presents examples for the successful suppression of torsional resonances in synchronous machines of an isolated power system based on flywheel generators and by three phase fault in the second benchmark model of the IEEE.**

Keywords: **Subsynchronous Oscillation, active damping, torsional vibrations**

I. Introduction

SUBSYNCHRONOUS Oscillation (SSO) is defined by the IEEE subsynchronous resonance working group as an electric power system condition where the electric network exchange significant energy with a turbine-generator at one or more the natural frequencies of the combined system below the synchronous frequencies of the system which following a disturbance from equilibrium.

Subsynchronous Resonance (SSR) is usually discussed in case of power system with turbine generator and series compensated transmission lines. But according to the definition of SSO, a synchronous resonance can also result from the interaction of a turbine-generator with fast acting controllers of power system components. Two examples are investigated with a developed Parallel Connected Damper Circuit (PCDC) as a stabilizer for oscillating torques in synchronous machines using inductive energy storage or capacitive energy storage. In the first case we investigate the experimental power supply of Max-Planck-Institute for plasma physics in Garching Germany (Fig. 1) and in second case the IEEE second bench mark model (Fig. 2).

The research at IPP concentrated focus on nuclear fusion. 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 a very high temperatures to ignite the fusion fire [1].

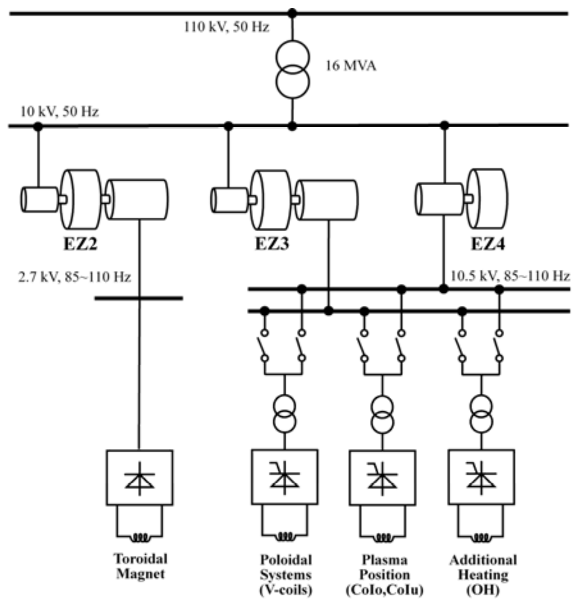

Fig. 1. Structure of the IPP experimental power supply

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 order to magnetically confine the plasma, high DC currents (up to 70 kA) are necessary in the toroidal and poloidal magnetic field coils.

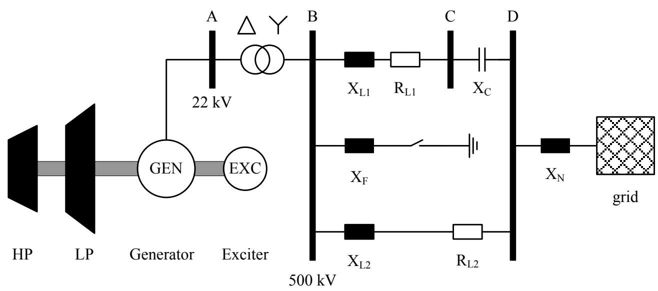

Fig. 2. IEEE Second Benchmark: Example for a classical SSR phenomenon

The power supply for the magnet coils and additional plasma heating systems requires an electrical power up to a

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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. 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. 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 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 [3] 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. 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 III.

III. Development of the Dynamic Stabilizer for Oscillating Torques

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

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

Where

$\phi(t)$	torsion angels of the shaft
$u(t)$	externally applied torques
J	matrix of moments of inertias
D	damping matrix
K	stiffness matrix
B	input matrix for the 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. 3. The torsional velocity is electronically derived from a torque sensor measurement in the block "Control System for Signal Modification". Fig. 3 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.

For development and optimization of the torque stabilizer a

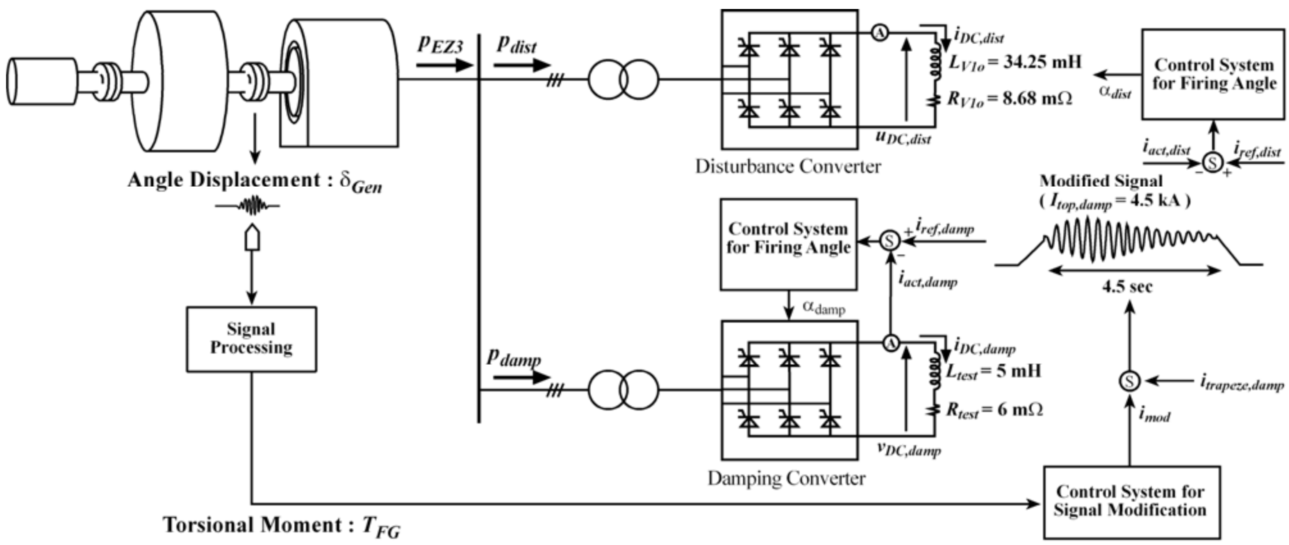

Fig. 3. Schematic of the test setup for excitation and damping of torsional oscillations in the assembly of generator EZ3

numerical simulation model was derived using the program package Simplorer [4]. 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 [5]. 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 (Fig. 4) and integrated into the generator model based on dq0 parameters [6]. The differential equation system of the mass-spring model was derived from single torque equations as given in (1) 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 (2):

$$\omega_{Mot} = \frac{1}{J_{Mot}} \int \left(T_{Mot} - T_{MF} \right) dt$$

$$\omega_{FW} = \frac{1}{J_{FW}} \int \left(T_{MF} - T_{FG} \right) dt$$

$$\omega_{Gen} = \frac{1}{J_{Gen}} \int \left(-T_{el} + T_{FG} \right) dt \qquad (2)$$

$$T_{MF} = K_{MF} \int \left(\omega_{Mot} - \omega_{FW} \right) dt$$

$$T_{FG} = K_{FG} \int \left(\omega_{FW} - \omega_{Gen} \right) dt$$

Where

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

T_{FG} torque excerted at the 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.

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})

A typical result from operating the active damping circuits during ASDEX Upgradeplasma experiments is shown in Fig. 5 and Fig. 6. 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, reaching a value of 1.11 MNm. That value corresponds to an active power of 175 MW at a generator speed of 1500 rpm and caused the EZ3 torque sensors to send a trip signal. In Fig. 6 active damping was provided by means of a parallel connected damping circuit with a 1 mH-inductor.

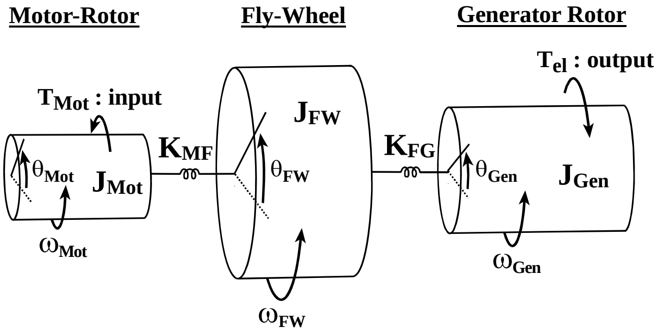

Fig. 4. Mass-spring model of the EZ3 shaft system

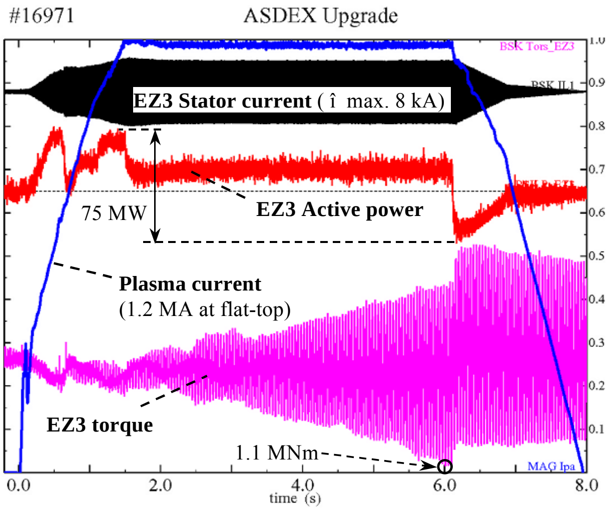

Fig. 5. Measured EZ3 generator current, active power and torque showing a torsional resonace excited by active power transients during AUG plasma experiment #16971

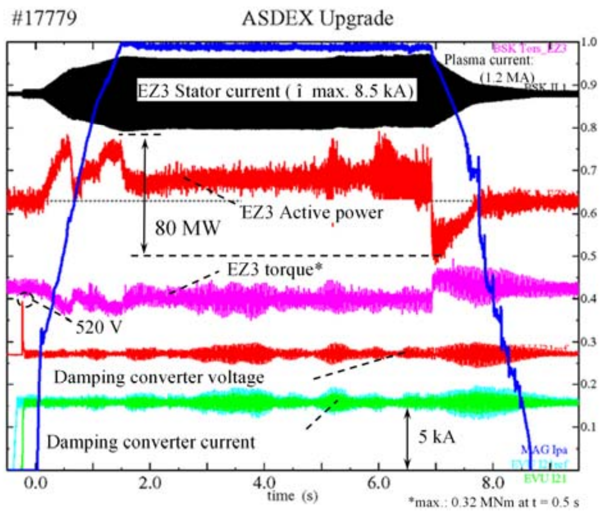

Fig. 6. Stabilization of the oscillating torque caused by a plasma experimental comparable to #16971 in using the EZ3 torque stabilizer at low operational gain (damping power < 1 MW)

It can be seen at $t < 0$ s, 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.

IV. 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. Fig. 6 shows an example design for a shaft assembly of a turbinegenerator (IEEE Second Benchmark Model for Computer Simulation of Subsynchronous Resonance [8]). The turbine-generator has a nominal power of 600 MVA. 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:

$$f_{nat} \quad 24.65\text{ Hz}\ ,\ 32.39\text{ Hz and } 51.10\text{ Hz}$$

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 a single generator shown in Fig. 7 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 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 better comparison with the simulation results in literature [7], 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.

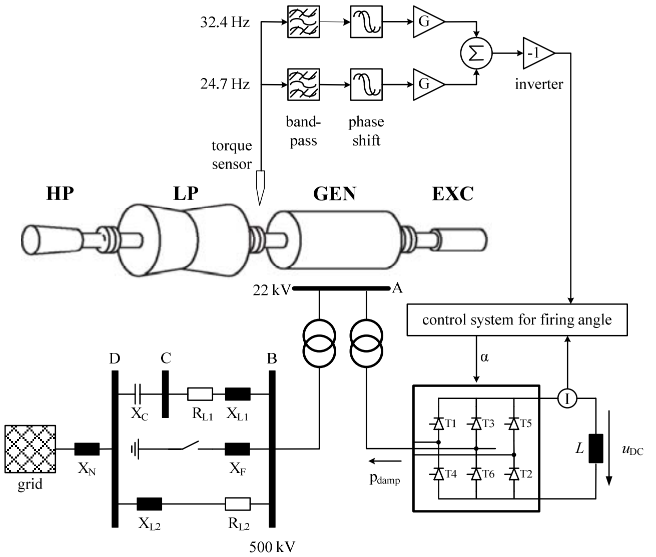

Fig. 7. Electrical network representation of the IEEE Second Benchmark Model for SSR simulations and active damping circuit for a turbine generator (with an extended control module for multi-mass system)

In Fig. 9 the same parameters concerning the model and the fault were applied but the active damping circuit shown in Fig. 7 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 occurence of 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.

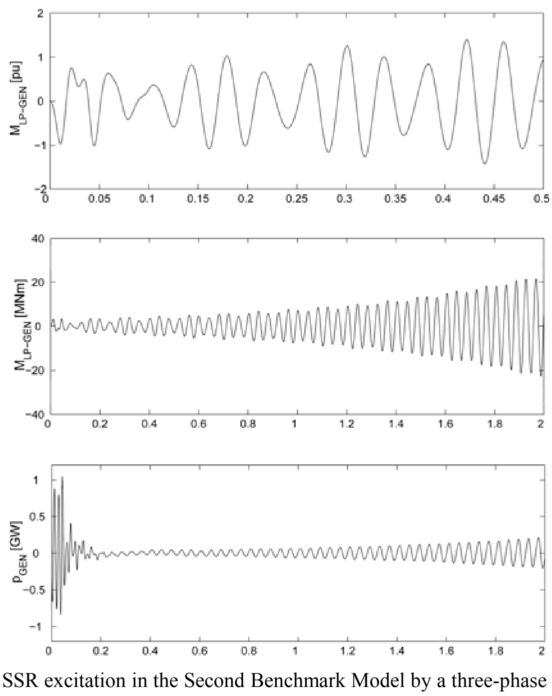

Fig. 8. SSR excitation in the Second Benchmark Model by a three-phase fault (clearing time 40 ms)

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 (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.

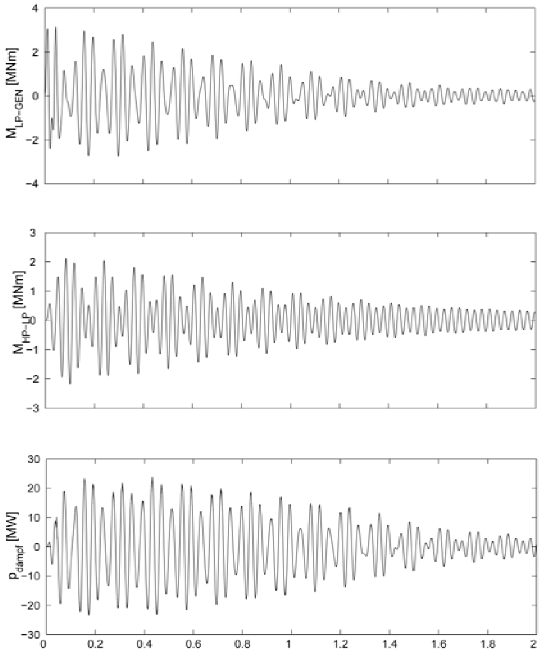

Fig. 9. Active damping of SSR case shown in Fig. 8 (damping circuit configuration shown in Fig. 7)

V. PCDC With Capacitive Energy Storage

The so far presented Parallel Connected Damper Circuit based on a six-pulse thyristor bridge and inductive energy storage has various disadvantages. The main point is the restricted frequency range of the damping power. The maximum damping frequency is limited by the line frequency, because of the line commutation of the thyristor bridge.

Besides the frequency limits there are some other disadvantages of this system. An application of the PCDC at machines with a nominal voltage in the high voltage range would be relatively cost-intensive. In order to be able to buffer sufficient energy in the inductive storage one has to install either a converter transformer to reduce the maximum output voltage of the rectifier or to implement a high voltage coil with big dimension. Another drawback is the reactive power demand of this system. To assure a high dynamic of the damper circuit at anytime, it is necessary to keep the coil charged i.e. the coil and the rectifier is current-carrying (i_{DC}). At this standby-mode the bridge would permanently absorb the reactive power according to

$$Q_{standby} = \frac{\sqrt{18}}{\pi} \cdot U_N \cdot I_{DC} \quad (3)$$

Furthermore the line commutation always generates undesired harmonics in the line currents.

Most of the described drawbacks can be compensated by using a PCDC with capacitive energy storage. In this case it is necessary to use a self-commutated converter with sheddable valves, e.g. Mosfet, IGBT, or IGCT.

Fig. 9. shows the basic configuration of a self-commutated three phase inverter with a capacitive electric energy storage.

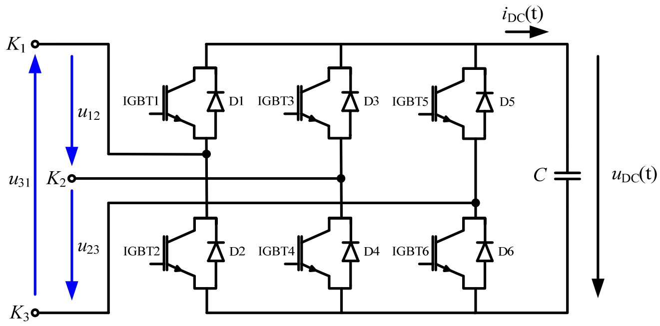

Fig. 10. Three phase self-commutated inverter with IGBTs and capacitive energy storage

Let us assume a constant voltage u_{DC} of the capacitance C. By a suitable switching of the valves a three phase voltage of variable amplitude, phase and frequency can be generated at the clamps K_1, K_2 and K_3. Thereby the line-to-line voltages u_{12}, u_{23} and u_{31} are pulsed square wave signals with the voltage levels $-u_{DC}$, $+u_{DC}$ and 0 V. The average values of this pulse pattern result in sinusoidal voltages. If the inverter is coupled to a synchronous machine with two three phase systems are interlinked via a reactance X. A simplified equivalent network is shown in Fig. 10. There, the output three phase voltages u_G and u_{WR} of the generator and the inverter are represented as ideal monophase voltage sources.

In power delivery the current i and the voltage u_G have the equal sign and the angle δ is negative (solid arrows in Fig 11). By contrast the angle δ is positive and the sign of i and u_G are opposed for power absorption by the damper circuit (dashed arrows in Fig. 11).

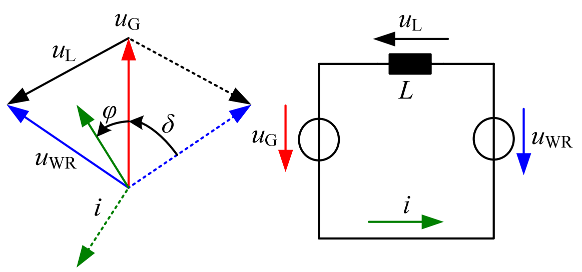

Fig. 11 Monophase equivalent network of the system with vector diagram

An optimal energy balance could be realized by maintaining the current i and voltage uG always in-phase so that there is only an interchange of active power. Therefore it is advisable to consider the current i as the control parameter of the inverter. In a three phase grid the active power is calculated form the actual values of the phase voltages and the phase currents according to

$$p(t) = u_1(t) \cdot i_1(t) + u_2(t) \cdot i_2(t) + u_3(t) \cdot i_3(t) \qquad (4)$$

A modulation of the current as shown in (5)

$$\begin{aligned} i_1(t) &= \hat{u} \cdot \sin(\omega t) \cdot c \cdot p_{\text{damp\_ref}}(t) \\ i_2(t) &= \hat{u} \cdot \sin(\omega t + \frac{2\pi}{3}) \cdot c \cdot p_{\text{dam\_ref}}(t) \\ i_3(t) &= \hat{u} \cdot \sin(\omega t - \frac{2\pi}{3}) \cdot c \cdot p_{\text{dam\_ref}}(t) \end{aligned} \qquad (5)$$

leads to the damping power p_{damp}:

$$p_{\text{damp}}(t) = \frac{3}{2} \hat{u}^2 \cdot c \cdot p_{\text{damp\_ref}}(t) \qquad (6)$$

This means that the required phase currents are obtained by the modulation of the respective phase voltage with the desired value of the damping power $p_{\text{damp\_ref}}$. In the vector diagram of Fig. 11 now the voltages uG and uX are orthogonal and the angle φ is constant zero.

With the capacitive PCDC it is possible to generate damping frequencies above the line frequency. A frequency range of several hundred Hertz is conceivable. The efficiency of this PCDC is essentially improved because there is only a small demand for reactive power. In addition, the standby can be handled smoothly. The recharge current of the capacitor is also quite small in real applications. The costs of this PCDC with capacitor in comparison to a PCDC with inductor can be estimated to be significantly lower.

VI. 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.

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. To increase the restricted frequency range of the damping power and reduce the cost of required high demand for reactive power by required converter transformer, a damping system based on a PCDC with capacitive energy storage is activated. Therefore a self-commutated inverter with sheddable valves is required. The drive of the damping power was realized with a closed-loop control of the phase currents.

With the capacitive PCDC, it is now possible to generate damping frequencies above the line frequency. A frequency range of several hundred Hertz is conceivable. The efficiency of this PCDC is essentially improved because there is only a small demand for reactive power. In addition, the standby can be handled smoothy.

VII. Acknowledgment

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