Investigation Of The Stability Of A 600 MJ Energy Storage System Based On Paralleled Flywheel Generators

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Abstract

ASDEX Upgrade, an experimental tokamak device for nuclear fusion research, requires an electrical power up to a few hundred MVA for a time period of 10 - 20 s. The power and energy is provided by the three large flywheel generators. Considerations are under way to extend the existing power supply by a new energy storage system. A first study lead to the result that a parallel connection of about 40 commercially available flywheel generators would meet the future power and energy requirements (60 MW / 350 MJ at 110 - 85 Hz / 600 MJ at 110 - 60 Hz). The paper will present the structure of the modular energy storage system and results of numerical investigations (stability analyses, simulation of operating and fault cases) considering a group of two paralleled prototype units (6,6 MW / 38 MJ per unit), each unit consisting of four directly paralleled Powerbridge (PB) generators.

Introduction

On its way to a power plant, nuclear fusion research is concentrating on two different types of experiments, the tokamak and the stellarator. Most of the devices in the world today are of the tokamak type, which is best investigated and comes closest to the ignition conditions. The Max-Planck-Institut für Plasmaphysik, Garching, commissioned such an experimental device, called ASDEX Upgrade, in 1991. In this device the ring-shaped hydrogen plasma carries an electric current up to 1.4 MA. The magnetically coupled coils of the experimental device shown in Fig. 1 require an electric power of several hundred MVA for about 10 s [1]. Static converters powered by flywheel generators are used to feed the coils. During the next few years, ASDEX Upgrade will strengthen its efforts concerning investigations of advanced tokamak scenarios in connection with increased triangularity shaping and divertor operation. To fully exploit these operating modes a plasma current flattop time of at least 2-3 plasma skin times, i.e. 10 seconds, is required. For the power supply this means an increase of the pulse length by at least 4 s. In order to achieve this, the power factor must be improved, the apparent power distribution must be optimized and the available flywheel energy must be fully exploited.

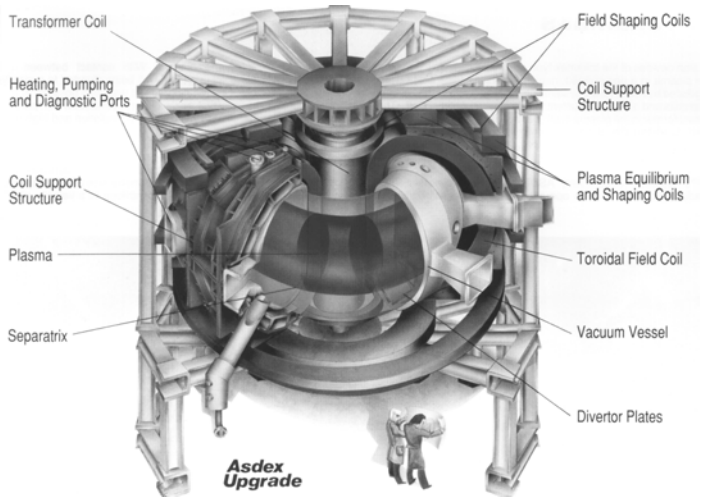

Fig. 1: ASDEX Upgrade tokamak

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Present power supply of ASDEX Upgrade

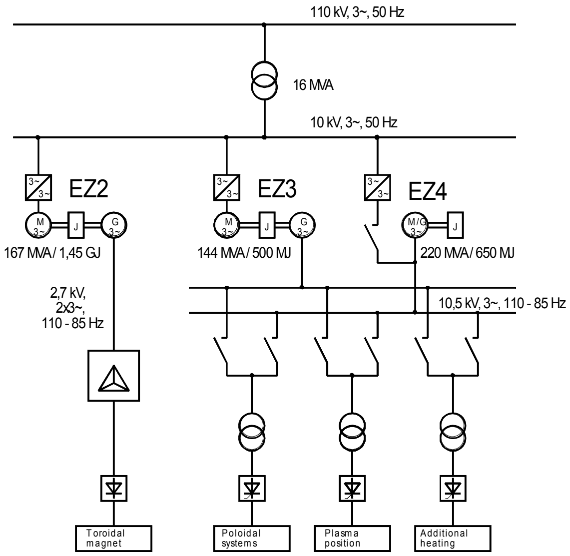
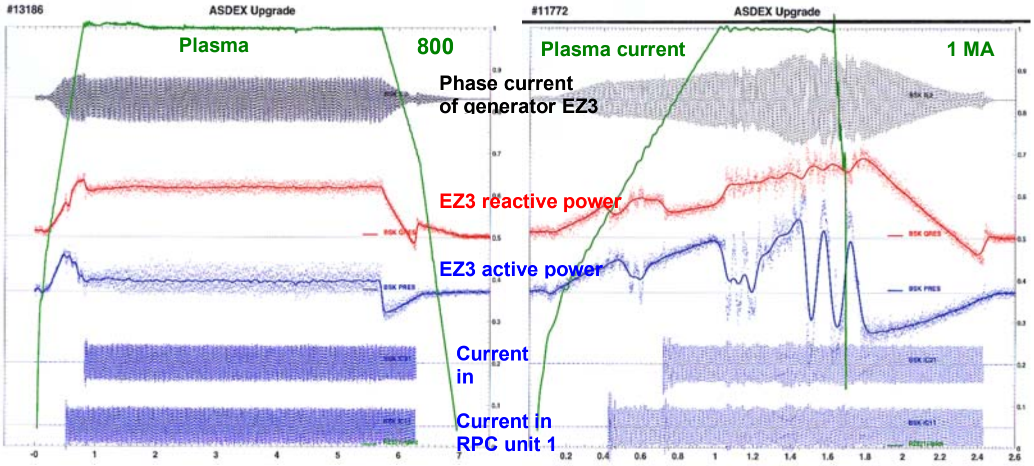


Fig. 2: Present power supply system of ASDEX Upgrade

The power supply of the ASDEX Upgrade (AUG) tokamak consists of three distribution systems (110-85Hz) as shown in Fig. 2, 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). So far, each synchronous machine has been feeding its own 10.5 kV grid. Before plasma experiments can be performed, each flywheel generator is accelerated within several minutes to maximum speed (up to 1650 r.p.m.) by means of a starting converter (EZ4) respectively a separate driving machine (EZ3), both being supplied from the utility supply (50 Hz) via a 16 MVA connection ("loading"). Then the generators are electrically disconnected from the utility supply. During the plasma pulse the flywheels are unloaded within seconds. The busbar voltages are kept at a constant value (10.5 kV) throughout the pulse. Thus, the energy needed for the experiment is taken only from the flywheels and the pulsed load is kept away from the utility supply. Operational phases of the flywheel generators supplying ASDEX Upgrade during plasma pulses are shown in Fig. 3.



a) Long pulse b) Short Pulse

Fig. 3: Load curves measured on generator EZ3 during plasma discharge

The large inductive voltage required by the coils 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 power factor drops from 0.6-0.8 during the plasma current rise to 0.2-0.3 during the plasma flat-top. Fig. 3.a shows typical time histories of the plasma current, a phase current of generator EZ3, and the active and reactive power supplied by that generator during a typical plasma pulse. In 2001 a 120 MVAr SVC system consisting of eight RPC modules was installed and commissioned in the network of generator EZ3 which is not capable of supplying such large amounts of reactive power. The characteristics of the reactive power load curve during plasma pulses was the determining factor for the decision to compensate reactive power by capacitor banks energised with line synchronised vacuum breakers which is more economic than thyristor controlled compensat-ion [2]. The capacitor currents in two of the compensation (RPC) modules are shown in the lower part of Fig. 3.a and

3.b. Normally, the power demand of a tokamak experiment can be characterised by a high active power (p) demand 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 (Fig. 3.a). However, plasma feedback control can cause fast changes of the p demand in the power supply. Fig. 3.b gives an impression of the p demand occurring under fault conditions (disruption at $t = 1.63$ s). Extreme power demands must be the basis for the design of the power supply system.

Parallel operation of EZ3 and EZ4

For quasi-stationary advanced tokamak experiments with extended plasma flat-top phase, the power systems of EZ3 and EZ4 must be connected in parallel, so that full advantage of the installed generator power and flywheel energy can be realised. This requires for the two 10.5 kV / 100 Hz networks to solve two major problems: Optimisation of the power sharing between the two generators, this function being achieved by a voltage / power controller and optimisation of the energy sharing between the two generators which will be achieved in having a single system frequency (provided that the system is stable [3]). Detailed engineering of the control and power schemes has been elaborated in cooperation with industry.

For the parallel connected power supply of EZ3 and EZ4, it must be assumed that the amplitude of active power oscillations can be two or three times higher than shown in Fig. 3.b. Such active power oscillations require high efforts with respect to stability and the exciter current feedback control of the generators.

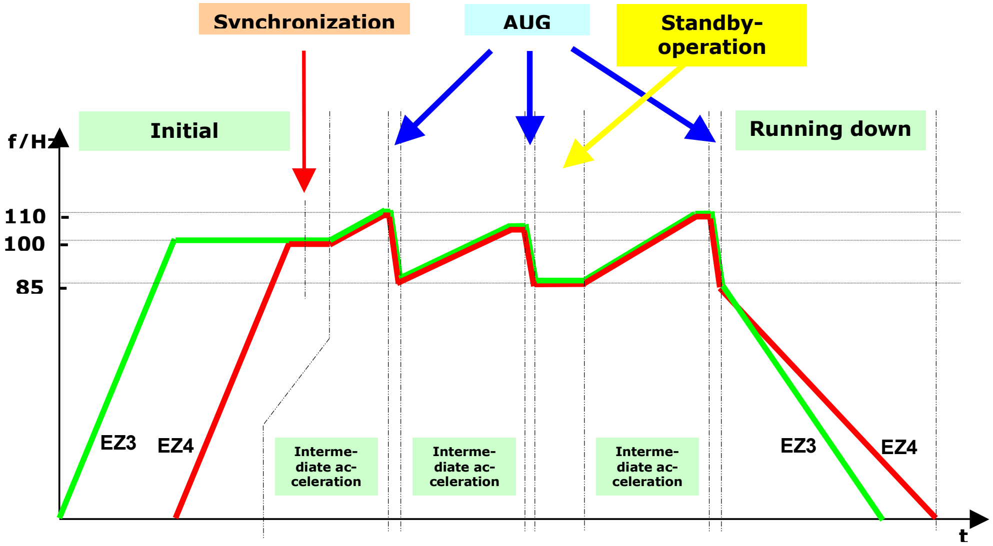


Fig. 4: Operational phases of EZ3 and EZ4 supplying ASDEX Upgrade

Despite of the problems to be solved because of extreme load requirements and the different electrical and mechanical parameters of the machines (EZ4: motor-generator built in 1987; EZ3: generator with separate driving machine built in 1977), the paralleling of the generators is advantageous for the future development of ASDEX Upgrade for the following reasons:

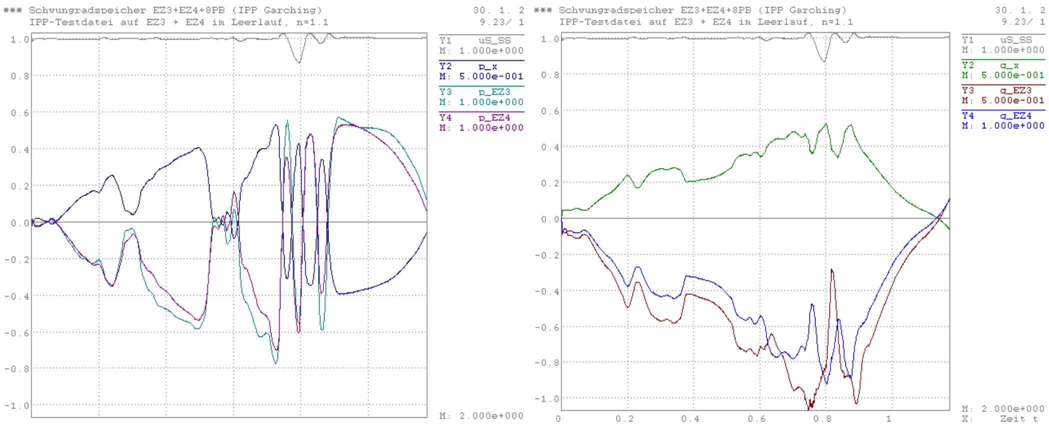
- The flywheel energy can be fully exploited without overloading one of the generators (exploitation of energy)
- Instead of boundaries from limits of the single machines the maximum power will be 350 MVA (exploitation of apparent power installed)
- Improvement of power quality because the parallel connection brings a reduction of the subtransient reactance
- The reactive power compensation modules installed at generator EZ3 would be available for both generators
- The parallel connection of EZ3 and EZ4 provides a better base for extending the system
- The realization is planned in such a way that both generators can be operated as single machines if problems arise

Before the synchronization process, both flywheel generators must be brought to about the same rotational speed with their driving systems (see Fig. 4).

After disconnection of the EZ4 starting converter a correction of differences in frequency or the phase angle can be realised by means of the EZ3 driving machine. The synchronization is most favourable at high network frequencies to keep electrical transients as low as possible.

The active power distribution among the two flywheel generators will be proportional to the kinetic energies of the masses of inertia. Fig. 5 shows the time histories of the busbar voltage, the active and reactive power of the paralleled generators EZ3-4 assuming a test load corresponding to the EZ3 load shown in Fig. 3.b.

The inertia constants related to nominal apparent power are H_{EZ3} = 7.7 s and H_{EZ4} = 6.7 s, so that EZ3 is loaded comparably higher with active power than EZ4 (Fig. 5.a). Since the rated power factor of EZ4 (cosφ= -0.49) is significantly smaller than the one of EZ3 (cosφ= -0.86), the load distribution related to nominal active power will be of ratio 2:3 among EZ3 and EZ4. I. e. related to active power the performance of the parallel connection will be limited by EZ4. This is not critical for ASDEX Upgrade because the experiments are conducted at low power factor.



a) Active power **b) Reactive power**

Fig. 5: EZ3 + EZ4 with test load (load comparable to Fig. 3b)

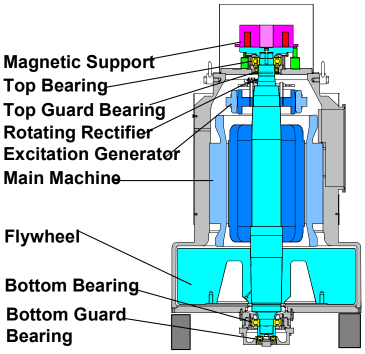
A suitable reactive power distribution among EZ3 and EZ4 can be realized by means of a reactive power controller applied to the voltage feedback control (Fig. 5.b). Because of limited exciter ceiling voltages the busbar voltage cannot be kept at a constant value as a consequence of the high reactive load. Good results were achieved in performing numerical simulations with a multi-variable controller [3].

Modular extension of the power supply

In addition to paralleling EZ3 and EZ4 it is planned to extend the power supply by additional energy storage systems to meet future requirements from the experiment (long pulse operation of ASEDX Upgrade) and to improve the security and effectivity of the supply. In order to

- keep the required investments at a reasonable level
- be able to split the investments over several years,
- keep the costs for maintenance and repair as low as possible,
- and to achieve a high degree of flexibility,

the extension shall be realised step by step in installing several identical modules based on standard components. The flywheel generators of RWE Piller GmbH type *Powerbridge (PB)*, see Fig. 6, each with 1.65 MW / 16.5 MWs, H_{PB}= 22 s, cosφ= -1.0 at 3x800 V, 60 - 110 Hz, seem to be suited for that purpose.



Technical Data:

Net. energy content	16.5 MWs
Input/output power	1650 kW
Speed range	1800 to 3300 rpm
Total weight	6000 kg
Rotor weight	2900 kg
Idling losses	10 kW
Greasing frequency	permanent
Bearing service life	8 years

Features:

- Helium filled
- Magnetic support
- Redundant bearings

Fig. 6: Powerbridge (PB) - Schematic, specification and side view

Because of limited capability of the circuit breakers on the 800 V-side, 4 PB modules shall form a group of directly paralleled machines which feeds the 10.5 kV system by means of a transformer (Fig. 7). In the final stage the system would consist of ten groups (units), each with four PB modules.

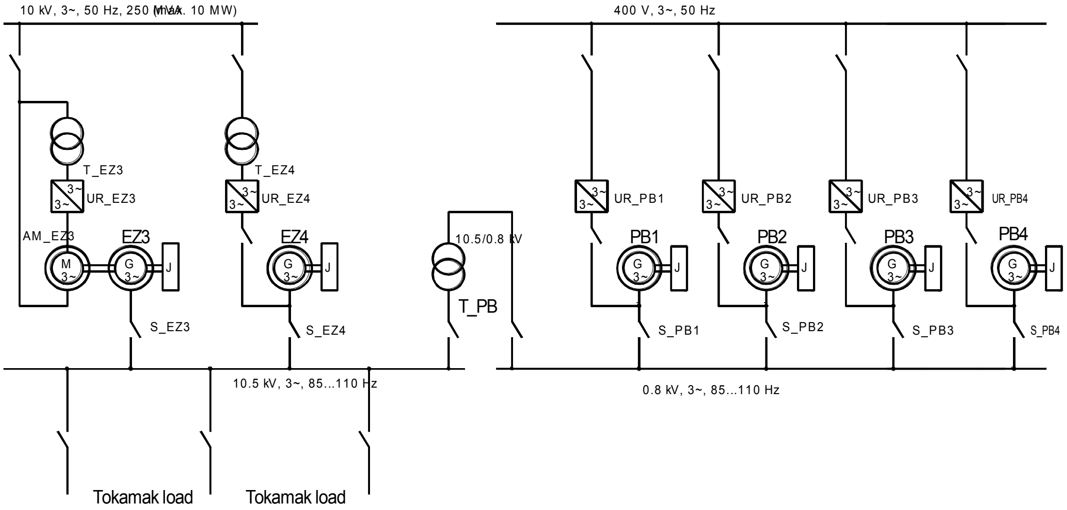


Fig. 7: Outline of future tokamak power supply

Having performed numerical simulations considering EZ3, EZ4 and PB modules, the synchronisation of the single Powerbridges which will be driven to working speed by starting converters and the joint acceleration ("loading") of paralleled PB units and EZ3-4 does not seem to be problematic. Fig. 8 shows the acceleration phase ("loading") from 85 Hz to 110 Hz using the 7.5 MW driving machine of EZ3. All curves, the 10.5 kV busbar voltage, the almost identical rotational speeds of EZ3 and a group of 8 PB modules, the stator current amplitudes, and the exciter currents of EZ3, EZ4 and the PB group, are given as p.u. values. The loading process takes about 240 s.

Since the PB modules are designed for pure active power loads, the parallel operation of EZ3, the PB modules and EZ4 will result in an active power distribution of the ratio 2 : 2.4 : 3 (related to nominal active power). Fig. 9 shows the dynamic behaviour of the system at an assumed step load of 360 MVA, cosφ= 0.68, at n= 1.0, without consideration of the reactive power compensation system. Although the transient reaction is not completely finished after 1 s, the active power curves show that EZ4 is overloaded (p_{EZ4}= - 0.682 p.u. compared to p_{EZ4r}= -0.49) whereas, with respect to reactive power, EZ4 is still below the maximum allowed values (q_{EZ4r}= -0.87 p.u. compared to q_{EZ4}= -0.79 p.u.). The reactive power controller of the PB modules is working very well. The active power overload of EZ4 is not critical because ASDEX Upgrade cannot cause loads of 360 MVA, cosφ= 0.68 and the short-time (1 s) capability of EZ4 is 260 MVA (compared to S_r = 220 MVA for 6 s).

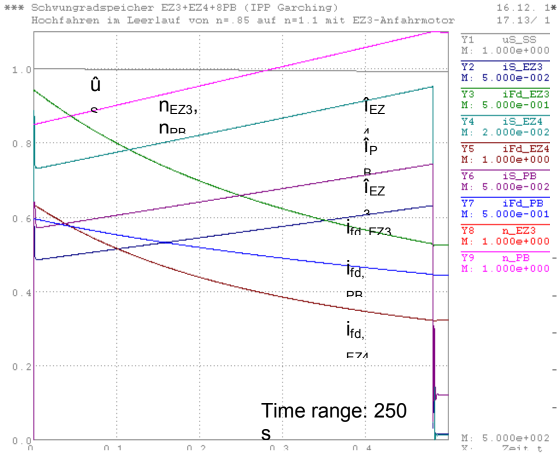


Fig. 8: Joint acceleration of EZ3+EZ4+8xPB

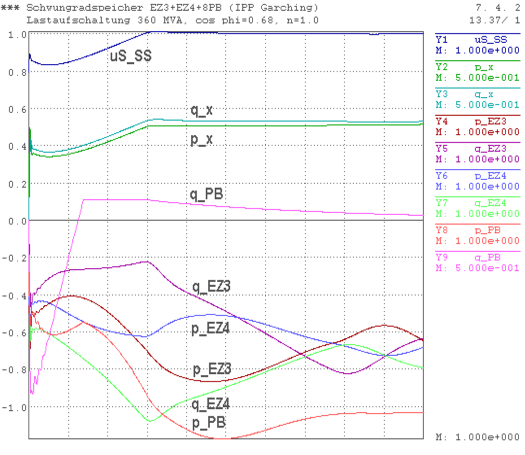


Fig. 9: Loading of EZ3+EZ4+8xPB with 360 MVA

Conclusion

The paralleling of the two flywheel generators EZ3 and EZ4 has distinct advantages for the future development of ASDEX-Upgrade if only by solving two major problems: Optimisation of the power loading between the two generators, this function being achieved by a voltage / reactive power controller and optimisation of the energy loading between the two generators, by the fact of having a single system frequency. However, the sum of available active powers from both machines cannot be fully exploited because of different inertia properties of the two machines. This is not critical for ASDEX Upgrade since the plasma experiments are conducted at low power factor.

Flywheel generators of type *Powerbridge* seem to be suited for a stepwise extension of the EZ3-4 flywheel energy storage system by 350 MJ altogether. For that purpose 10 groups with 4 machines would be required. Since high active and reactive load variations can occur during ASDEX Upgrade plasma experiments, a fast feedback control of reactive power is required to achieve a stable parallel operation of the flywheel generators EZ3, EZ4 and Powerbridge modules.

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