Perceptions about new kinds of subsynchronous resonances

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Abstract - **Subsynchronous resonance (SSR) phenomena are usually discussed in case of systems with turbine generators and compensated transmission lines. The present paper offers an entirely new point of view to the subject of SSR. It is shown that this phenomenon does not only occur in the mentioned but also in other cases, where it can also cause severe damages to machines and equipment. Three examples of SSR that appeared in actual power systems are presented, analysed and discussed. As a result, SSR is a much more diversified subject than usually supposed. It has to be considered more emphasized and may possibly occur in all kinds of power systems where synchronous generators supply any kind of load.**

Keywords: SSR, turbine generator, slip ring induction machines, thyristor cascade, 2D numerical field calculation.

I. INTRODUCTION

SSR phenomena have been in the centre of interest since many years, and the subject has always been discussed in a multitude of publications (e.g. [1], [2], [3], [4]). Up to now only systems consisting of one or more turbine generators feeding a long compensated transmission line where severe damages occured have been investigated. But in the last few years it became obvious that also other circumstances or conditions can lead to an electro-mechanical resonance without capacitors being used to compensate transmission lines. These phenomena, where also damages can occur, are also found quite often. So it is reasonable to investigate them more closely. For this reason the following cases will be presented in this paper: an example for the usually well-known SSR phenomenon, SSR caused by feedwater pumps fed by thyristor cascades, electro-mechanical resonance during running up of a squirrel cage induction machine and totally new: SSR caused by slip ring machines with faulty rotor windings connected to a close meshed private power system with synchronous generators.

As a purpose an overview of different kinds of SSR is given, with a special emphasis on the new kinds of SSR that we found.

II. USUAL SSR PHENOMENA

The usual SSR phenomena caused by compensated transmission lines can be manifested in three forms: Induction generator effect (IGE), torsional interaction (TI) and torque amplification (TA). These phenomena may occur isolated or simultaneously, and when they occur they can cause damaging oscillations. Hazardous levels might be reached within 0.1 seconds.

Possible SSR countermeasures are also well known. There are two basic types: unit tripping and non-unit tripping. Unit tripping countermeasures are e.g.: torsional motion relay, armature current relay or unit tripping logic schemes. Non-unit tripping devices are e.g.: static block filter, dynamic stabilizer, series capacitor bypassing or thyristor controlled series compensation.

Now a classical example where SSR occured is presented. The investigations were done on an actual power station in Central America. The station is connected to a 400 km long compensated transmission line with 345 kV rated voltage. At the end of the line the power is transformed to 220 kV and then fed into the grid. A model as shown in fig. 1 was used for the investigations. The system model was mainly focused on a detailed representation of the compensated transmission line and the electro-mechanical characteristic of the two GT and the one ST generator unit.

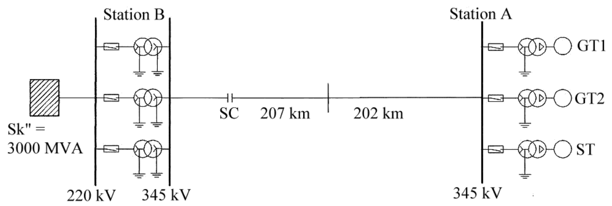

Fig. 1. Investigated power system with classical SSR

The transmission line model includes the V- and Y-tower types and the line transposition. Its full line impedance matrix was calculated based on the geometrical wire arrangement. As a result the line has a calculated compensation degree of 69%.

A schematic of the steam turbine generator shaft system is shown in fig. 2. The main parameters are the inertia of the individual turbine and generator masses and the torsional stiffness of the shaft sections between the turbine and the generator sections. To calculate the torsional oscillations in the shaft system it was represented by a model comprising 136 masses and 135 springs.

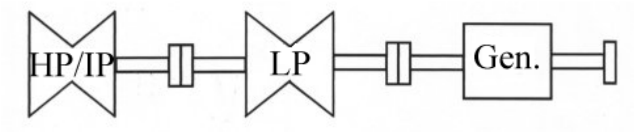

Fig. 2. Schematic diagram of steam turbine shaft system

The results of the eigenvalue analysis are the natural frequencies and the eigenvectors (see fig. 3). Within the range of 200 Hz for the steam turbine three natural frequencies were identified, i.e.: 18 Hz, 44 Hz, and 166 Hz. The first two are of interest for the SSR analysis. The gas turbine has its first torsional mode at 12 Hz. This mode can only be excited, as shown later, by compensation degrees above 90%.

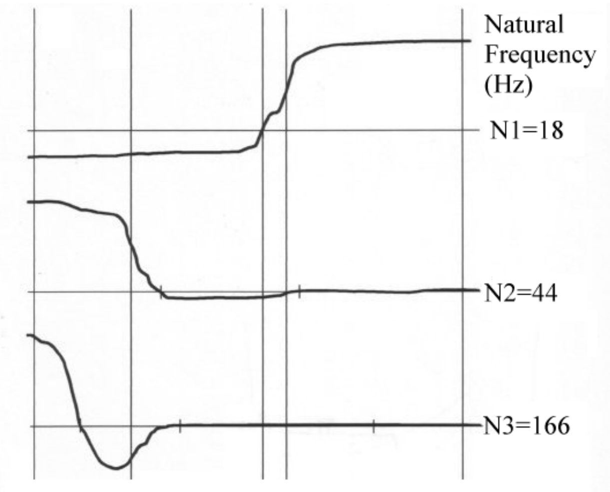

Fig. 3: Modes of the steam turbine generator shaft system

The coupled electromechanical calculation of the complete system was done by means of the NETOMAC® [5] program. To reduce the degree of freedom for the torsional calculation, the turbine generator shaft was represented by three masses and two springs. This representation still allowes the detection of the two lowest modes which are fully adequate both for the fault analysis and the SSR calculation. The natural frequencies calculated for the reduced model are also 18 Hz and 44 Hz.

Now system damping is decisive in assessing the severity of a fault. Within this context, the collective term "damping" denotes the combined effect of influences due to material damping, damping from windage, damping in bearings and electrical damping. A quantitative assessment of the magnitude of damping has been possible only on the basis of extensive measurements and tests at actual power stations [6]. Thus the modal analysis was used to consider the measured damping values in the calculation. The damping was described by the logarithmic decrement THETA. From this the modal damping can be easily calculated. Here THETA was assumed as:

for mode 1: $\vartheta_{m1} = 0.0025$
for mode 2: $\vartheta_{m2} = 0.0025$

These empirical values are rather small than large and therefore valid only for low stresses.

For calculation of the electrical resonance, the structure of the electrical system according to fig. 1 can be represented by a reduced model. The resonance frequencies depend on the short circuit capacity of the main system (fig. 4). For the analysis of SSR it is necessary to evaluate electrical frequencies close to:

for the steam turbine: $f_n - f_m = 50$ Hz - 18 Hz = 32 Hz
for the gas turbine: $f_n - f_m = 50$ Hz - 12 Hz = 38 Hz

where f_n is the electrical frequency and f_m is the mechanical resonance frequency. It shows that for S_k''=1000 MVA only the steam turbine can be excited at high compensation degrees above 90%. For more realistic assumptions of S_k'' =3000 or 5000 MVA there is a danger of SSR for both the gas turbine and the steam turbine.

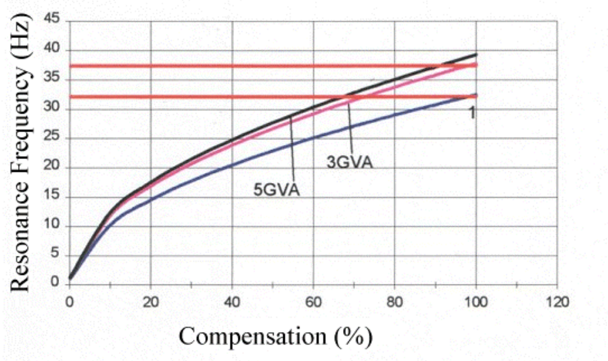

Fig. 4. Resonance frequencies of the main system

So detailed calculations were carried out for 4 cases:

- 1-phase fault at station A line end with 1-phase autoreclosure of the entire 345 kV line
- 3-phase fault close to station B at 200 kV
- 3-phase remote faults to station B at 200 kV with residual voltage of 80% and 90% at the 220 kV bus

As a result, for all cases SSR occured. So in the next step the total system damping has to be determined. The basic for this are the fault cases. Calculations were again carried out with the NETOMAC® program. For all cases the compensation degree was varied between 50% and 110%. The damping decrement was calculated according to $\vartheta_{mi}=-(1/N)*\ln(A_{i+1}/A_i)$. A_i was determined at the beginning of the torsional oscillations at t = 2 sec. A_{i+1} was determined at the end of the calculated period t = 6 sec. The results are: Negative damping for compensations above 60% in fault case 1 (see fig. 5). At the planned nominal compensation of 69% the damping is -0.015. For compensation degrees beyond 90% the negative damping is obviously influenced by the gas turbine SSR. For case 2 the situation is quite similar. In case 3 and 4 the damping at 69% series compensation degree was again determined as -0.015. It can be concluded that the kind of fault and the fault conditions do not influence remarkably the electromechanical damping.

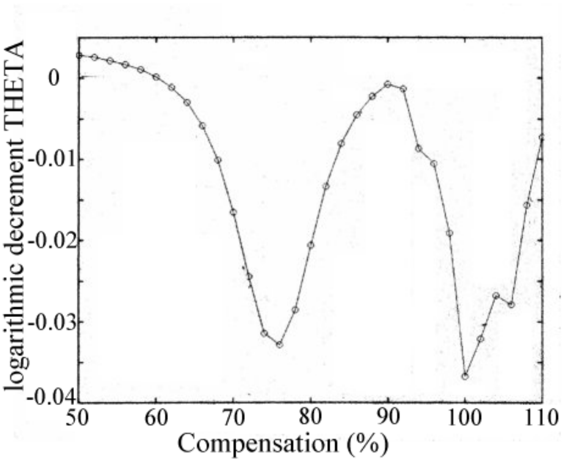

Fig. 5. Logarithmic damping decrement after 1-phase fault

So the following conclusions could be made: Any system faults with even small disturbances lead to severe SSR for series compensation > 60%. Between 60% and 90% compensation the steam turbine is involved. The power plant operation is not permissable without additional SSR countermeasures. An SSR protection relay as an only solution is not acceptable because any small disturbance would trip the turbine unit. But it is possible to operate the plant at a reduced load with 50% compensation degree before SSR countermeasures are installed.

III. SSR CAUSED BY FEEDWATERPUMPS FED BY THYRISTOR CASCADES

A quite different mode of excitation of subsynchronous natural frequencies in turbine generator shafts by subsynchronous components in the electrical torque was observed in a 775 MW turbine generator in Germany [7]. The SSR was detected by a torsional stress analyser (TSA). The boiler feedwater pumps of this power plant were driven by power-converter-controlled asynchronous motors as illustrated in fig. 6. With the turbine operating almost at full load, subsynchronous feedback from the converter cascade into the network caused pulsation in the electrical airgap torque of the generator of approx. 7% of rated torque and with a frequency of 16 Hz. This pulsation matched the first torsional frequency of the shaft system and excited torsional vibrations in the turbine generator. So this pulsation in the electrical torque was amplified by the oscillating generator rotor. Due to this resonance, torsional vibrations were stimulated with stresses slightly above the threshold of a preset endurance limit in the TSA. The supervised shaft torques were monitored, converted into fatigue increments and accumulated to shaft life expenditure by the TSA. Because this relatively small torsional vibrations were frequently induced, a high generator shaft life expenditure quickly accumulated, sparking off intensive investigations to find the cause of this torsional impact.

This example clearly demonstrates the importance of the fatigue endurance limit as a threshold between no damage and shaft damage, the significance to ascertain precisely the actual magnitude of the endurance limit and the problems resulting of even a small safety margin due to unavoidable uncertainties in material characteristics and stress analysis. In the case of resonance excited torsional vibration of rather small amplitude with a large number of load cycles it depends on only a slight variation in the magnitude of shaft torques whether or not loss of life or even shaft damage can occur. Such potential damage can only be reliably excluded by continuously monitoring the torsional duty of the shaft like it was done in the aforementioned case. After discovering the root cause of the torsional resonance at the 775 MW turbine generator any further excitation of resonant vibrations has been avoided by quickly passing the critical speed range of the feedwater pump. Stimulation of torsional subsynchronous resonance in connection with HVDC-systems has also been reported [8]. In this case the excitation mechanism are likewise originated in the controlled rectifier and inverter current banks.

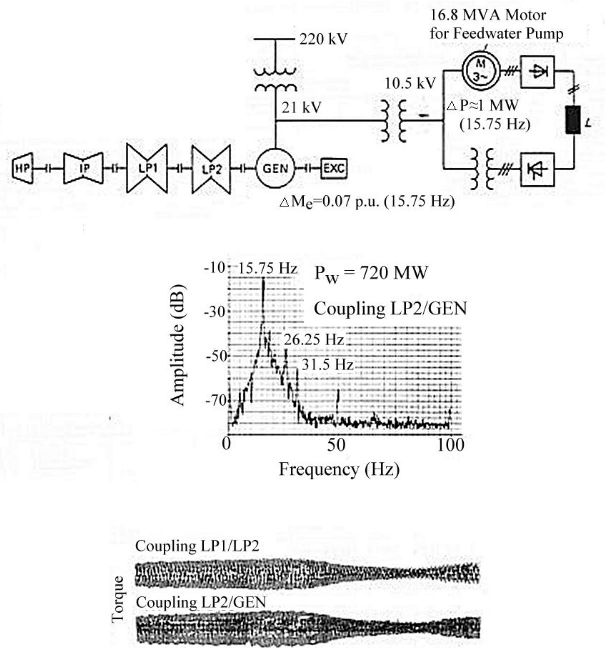

Fig. 6. Subsynchronous torsional resonance of a 775 MW turbine generator due to feedback from a thyristor cascade

IV ELECTRO-MECHANICAL RESONANCE DURING RUNNING UP OF A SQUIRREL CAGE INDUCTION MACHINE

In [9] an example for electromechanical resonance in case of a motor and main engine coupled via hitch and gear is given. A model of the investigated system is shown in fig. 7.

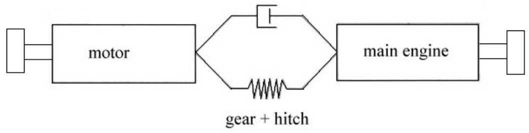

Fig. 7: Model for drive system

The numerical calculation of different types of drives brought an important insight: also in systems with induction machines an electromechanical resonance can occur, especially during running up. Consequently the torque in the connection components between motor and main engine can reach values much bigger than the maximum stationary breakdown torque (see fig. 8). This highly depends on the mechanical-geometrical and the electromechanical attributes of the entire system. Also the inner mechanical damping has to be considered. As a result, no gobal predictions about the endangerment of a drive system can be made and must not be made.

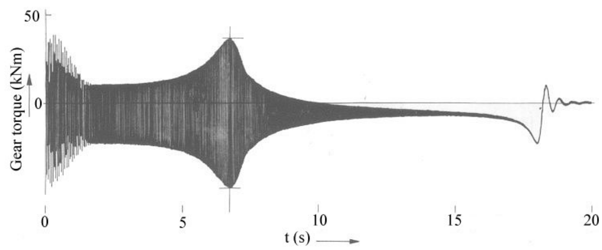

Fig. 8.: Calculated gear torque

Another example for electromechanical resonance in an squirrel cage induction machine configuration was investigated at the University of Dortmund [10]. It was again both measured and calculated. Calculation was carried out by using a numerical field calculation program which was developed and already successfully used at the institute for electrical machines, drives and power electronics at the Dortmund University. This program is based on the method of finite differences. Electrical machines can be simulated two-dimensionally taking electrical networks and different mechanical loads into account. The magnetic field within the machine's cross section as well as the electrical behavior of all network elements and windings and also the dynamic of all mechanical elements are calculated in small time steps of for instance 0.1 ms. Each new calculation is based on the last values of voltages and currents in the network elements, the magnetic vector potential within the machine's cross section as well as on the rotational speed and the torsional and air gap torques in the shaft. The method can take eddy currents and skin effects within massive conductible areas in the rotor as well as the saturation of iron in the rotor and stator into account. Several different rotor circuits can be simulated, even if the rotor winding is faulty like a turn to turn short circuit in the excitation winding of a synchronous generator or the interruption of one winding within a slip ring machine. This is possible by an integrated simultaneous calculation of the electro-magnetic and the mechanical system. A system of equations with about 9000 variables is determined for each time step. Most of the equations describe the spatial discretization of the field equations. Two types of field equations are considered. The eddy current equation is used in conductible areas and the Poisson or Laplace equation is used for the windings and laminated areas. Only a few equations describe the electrical network and the mechanical shaft system.

The investigated machine set was composed of three drives. Drive no. 1 is coupled via v-belt to machine no. 2. The shaft of this was connected to a DC-machine in no-load-operation. The machine no. 2 has an extremely synchronous behavior at 214 rpm. This can be especially seen when running up the stand-alone-machine fed by 3-phase-ac-power-controller.

At 214 rpm the machine levels off. Caused by this existing synchronous speed to the rotor an oscillating torque with a frequency depending on the machines rotating speed is induced. At zero-speed this torque has a frequency of 100 Hz, and at 214 rpm it is zero. At 418 Hz it is again 100 Hz and so on. Further on the eigenfrequency of the mechanical system is given to approximately 14 Hz. So while running up the described machine-set a nearly constant shaft oscillation at 240 rpm occurs. This is caused by the superposition of electrically induced oscillation and mechanical resonance, because at 240 rpm the oscillating torque has a frequency of approx. 12.1 Hz, which is quite near to 14 Hz. Because the resonance appears above the synchronous frequency, this case could be called "Super-Synchronous-Resonance".

V. SSR CAUSED BY SLIP RING MACHINES WITH FAULTY ROTOR WINDINGS

Next a totally new SSR caused by slip ring machines with faulty rotor windings connected to a closely meshed private power system with synchronous generators is presented. In a plant for natural gas liquefaction (fig. 9) some electrical machines were damaged at the same time. On the one hand the slip ring connection of a 7 MW induction machine tore off. This caused an arc and one rotor winding got out of function. On the other hand the shear pins at the shaft of three synchronous generators which supplied the private net tore off at the same time. The following hypothesis was assumed: SSR occurred during the running up of the slip ring induction motor which caused the tear off of the shear pins within the generator shaft. Extensive works and simulations of the entire system were done in order to evaluate this hypothesis.

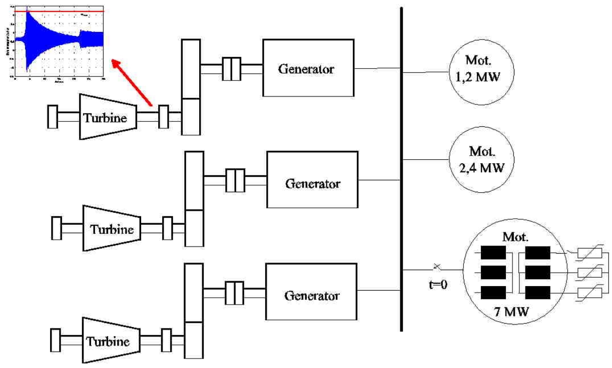

Fig. 9.: Plant for natural gas liquefaction

First in a test the time function of the stator currents for a 3 kW slip ring induction machine with an open rotor winding during running up were measured. The result was as to be supposed from the theory and as calculated: the stator currents had a transient component within the range from f_r = 60 Hz at n = 0 rpm to 0 Hz at n = n_{syn} = 1800 rpm (see fig. 11). The maximum amplitude of the electrical power during running up exceeds the nominal power more than four times and is also oscillating (fig. 10). In the actual system this takes effect on the shafts of the synchronous generators. As a result an electrical torque with variable frequency was generated in the air gap. This torque passed through all frequencies between 0 Hz and 120 Hz. So it crossed the eigenfrequencies of the shafts with 21 Hz and 84 Hz and excited the shaft to oscillation under resonance.

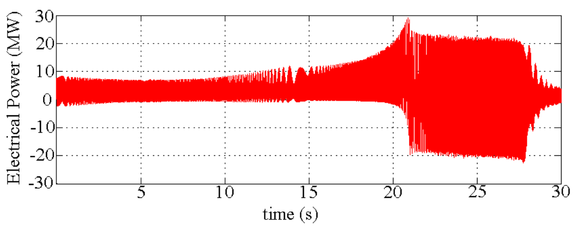

Fig. 10.: Calculated time-function of the electrical power fed by faulty slip ring machine

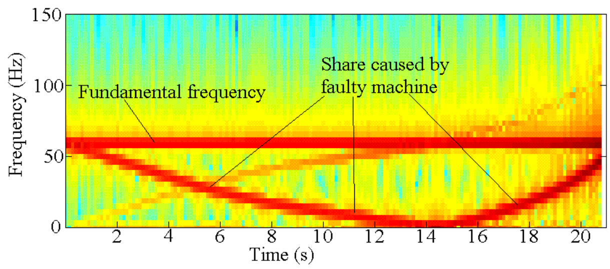

Fig. 11.: Calculated Spectra of current of a faulty slip ring machine during running up

To make sure that this hypothesis was correct, the complete system consisting of slip ring induction machines, synchronous machines and private power net was modeled and simulated. The simulation was carried out in two steps. First the rotor currents of the faulty induction machines were calculated. In the second step this currents were fed to the NETOMAC® program to calculate the torsional oscillations of the shaft. The calculation of the stator currents was done in two ways: First by using the already mentioned numerical field calculation program FELMEC and second by solving an system of differential equations.

This second method is much faster than the FD-program. But for the viewed case the usually well-known ODE-system for symmetrical states could not be used because of the fault in the rotor winding. So a new model had to be elaborated. That new equation system is given by:

$$[U]=[R][I]+[L]\frac{d}{dt}[I]+p\dot{\varphi}[L_{rot}][I] \qquad (1)$$

and

$$\Theta\ddot{\varphi}_{mech}+D\dot{\varphi}_{mech}=\frac{1}{2}\sum_{s=1}^{m+3}\sum_{k=1}^{m+3}i_s i_k\frac{\partial M_{sk}}{\partial\varphi}+m_a \qquad (2)$$

This can be derived by using the Lagrange-equation resp. the Hamilton-Principle. Equation (1) and (2) represent one of the most universal description of an induction machine for the fundamental wave. In addition, if neccessary, the harmonics can also be added. But this was not required in the investigated case.

The comparison of these to methods shows a very good agreement in the results for both the faultless machine and the faulty machine. To analyze the shaft oscillation caused by the currents, again the NETOMAC® program was used. As mentioned before, the generator shaft has to be modeled as a spring-mass-system. Here this was done by considering 13 masses and 11 springs to carry out the modal analysis. For the NETOMAC® program in turn a reduced model consisting of 8 masses and 7 springs was used. The eigenfrequencies which have to be considered for the SSR investigations are at 21 Hz and at 84 HZ. The damping was again supposed to be 0.0025 for both the first and the second mode of the shaft.

So the complete network of the plant has been modeled for the simulation:

- network with all controllers and protection systems
- all synchronous generators by using the Park Model
- generator shafts by a spring-mass-system
- imprinted currents of the faulty asynchronous machine

The load in the network during the simulation:

- three of five 8 MVA synchronous machines are in operation
- running up of one faulty 7 MW asynchronous machine, three other asynchronous machines (7 MW, 2.4 MW and 1.2 MW) in operation

The simulation is carried out for a time range of 40 seconds. The complete model is solved simultaneously for all machines. An example for the results is pictured in fig. 12. The course of the torsional torque (for 4 different masses of the spring-mass-system) during the running up of the faulty 7 MW motor is plotted. The torque shows two precise resonances. It equals 2.5-times the rated torque for the first resonance and 2-times the rated torque for the second. Additionally the running up of a faultless asynchronous motor was simulated. This calculation showed that no torsional torques occur besides the limits for this case. For this special case the maximal torque is even beneath the rated torque.

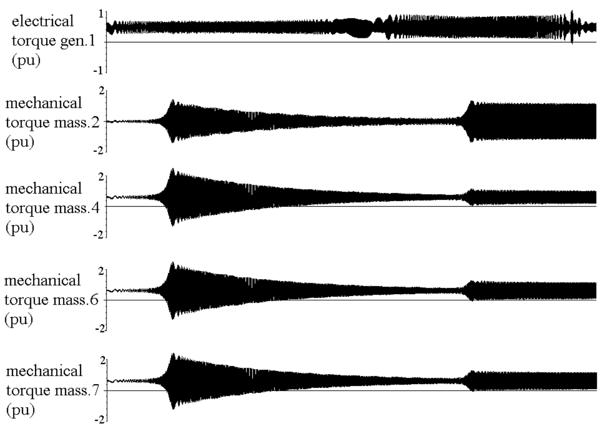

Fig. 12: Electrical and mechanical torque

So the calculated torque exceeds the tear off torque of the shear pins a little bit. Therefore it is not sure if the pin will tear off directly. Even if the pin will endure the stress, a severe fatigue of the material will occur in the shaft. Several running ups were performed with a faulty machine when the plant has been put into operation. This has led to a complete material fatigue and therefore to a tear off of the shear pins.

VI. CONCLUSION

The detection of new kinds of SSR has to be seen as a warning. The up to now known possible breakdowns only represent the current standard of knowledge. But it has to be reckoned that also other, yet not known breakdowns may occur. This has to be considered in the field of construction and protection measures.

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