HVdc generated SSR oscillations and SSR damping controllers in HVdc

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Abstract - **The nature of HVdc generated SSR - as opposed to SSR generated by series compensated AC lines - is described. Using the recently commissioned Kontek HVdc link as an example the design of an SSR damping controller in an HVdc control system is described. The tuning - through analogue simulation - is demonstrated. The test procedure to verify the function of the SSR damping controller during commissioning in various network configurations is described. At the commissioning of the Kontek HVdc link a series of SSR measurements were performed at the nearby Asnæs Power Plant, and the results of these measurements are presented. These results are compared with the theoretically expected results obtained from an analogue simulator. Finally the measuring technique is described as well as a first try at an alternative measuring method based on an FFT analysis of the generator phase currents.**

Keywords: SSR, SSDC, HVdc, Kontek HVdc link, Asnæs power plant.

I. INTRODUCTION

A. The SSR phenomenon

Subsybchronous resonance (SSR) in a generator-turbine shaft of a power plant is a phenomenon that can be present - unnoticed - for a long period of time and lead to a fatigue fracture of the shaft. As the name indicates the phenomenon is a resonance (at frequencies below the system frequency), and it occurs between the mechanical shaft system and one or more components in the electrical network. The phenomenon is most frequently observed in connection with power plants feeding into series compensated AC lines, but the phenomenon can also occur when an HVdc converter in the proximity of a power plant is operating as a rectifier.

The HVdc generated SSR occurs because the rectifier basically is a constant current load; hence there is no inherent damping associated with the converter. On the contrary the time constants associated with the HVdc system and epecially with the HVdc control system can generate negative damping in the low frequency range. If any of the mechanical resonance frequencies of the generator-turbine shaft are within this range there is a risk of SSR, and this risk is higher the lower the AC network damping is at these frequencies. For a further description of the HVdc related SSR phenomenon see [1], [2],[3],[4], and [5].

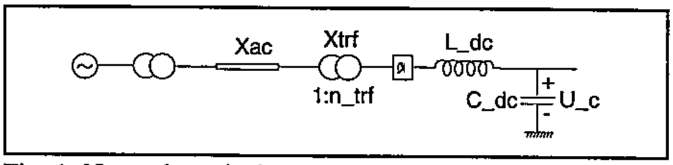

Fig. 1. Network equivalent.

II. Network model and nature of SSR

A. Network model

Experience shows that the HVdc related SSR problem is strongest when a power plant feeds directly into a rectifier via a radial connection. Experience also shows that the problem grows with the transmitted DC power and with the rectifier firing angle α. A mathematical explanation of this behaviour - based on a number of idealising assumptions - will be given in the following using the simple system in fig. 1. This configuration was actually tested during the recent commissioning of the Kontek HVdc link (between Eastern Denmark and North Germany) as will be explained later.

The cause of the SSR phenomenon is explained using a model where very simplified models of the involved components are used. The idea is to highlight the basics of the phenomenon rather than to give an exact and thorough description, and this is done by deriving a transfer function between the accelerating power at the generator and an applied disturbance in the DC current error I_{error} at given frequencies in the sub-synchronous range.

The generator (including step-up transformer) is modelled as an ideal voltage source with amplitude U_{AC}; i.e. exciter, stabilizer, governor, and impedances are disregarded. Further more the rotor inertia is considered to be very large; hence the rotor speed and the frequency is considered constant.

The AC line impedance is disregarded, and the converter transformers are represented by a constant transformation ratio n_{trf}. Hence all commutating reactance is ignored in this model. This simplifies the rectifier model a great deal. Thus according to [6] the converter is described by the following equations, and the differential equation for the DC current is:

$$U_{DC} = 3\sqrt{2}/\pi \; U_{AC} \; n_{trf} \cos(\alpha) \quad (1)$$
$$I_{AC} = \sqrt{6}/\pi \; I_{DC} \; n_{trf} \quad (2)$$
$$L_{DC} \; dI_{DC}/dt = U_{DC} - U_c \quad (3)$$

where α is the rectifier firing angle. The DC voltage over the cable capacitance C_{DC} is considered to be constant, since

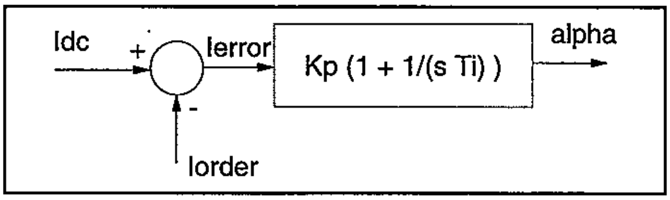

Fig. 2. Current control amplifier CCA

only the conditions in the rectifier network is discussed here. Further more the DC inductance L_{DC} is considered to be so large that the DC current can be considered constant in the small-signal analysis that follows.

As for the HVdc control system only the CCA (current control amplifier) in fig. 2 is of real interest here; the reason being that rectifiers normally are current controlling. This current control is handled by the CCA. The master controller that calculates the current order I_{order} of the HVdc link is disregarded in this context, hence the HVdc link is considered to be in current control. This is reasonable, since the master controller has a time constant in the range 0.1-1s, hence the master controller will only have very little impact on oscillations in the SSR range 10 - 50 Hz.

In the Laplace domain the CCA has the following transfer function:

$$\alpha(s) = K_P\,(1 + 1/(T_I\, s)\,)\; I_{error}(s) \tag{4}$$

Using (1)-(2) the accelerating electrical power P_{acc} at the generator rotor from the rectifier can be calculated as a function of α for small variations of α around an operating point α_{ref}:

$$\begin{aligned} P_{acc} &= \sqrt{3}\; U_{AC}\; I_{AC}\; (-\cos(\alpha) + \cos(\alpha_{ref})) \\ &= 3\,\sqrt{2}/\pi\; U_{AC}\; I_{DC}\; n_{trf}\; (-\cos(\alpha) + \cos(\alpha_{ref})) \end{aligned} \tag{5}$$

B. Derivation of transfer function

In order to be able to derive a transfer function for a small-signal analysis (5) is linearized around the operating point α_{ref}.

$$\begin{aligned} P_{acc} &= 3\,\sqrt{2}/\pi\; U_{AC}\; I_{DC}\; n_{trf} \cdot (\alpha - \alpha_{ref}) \cdot \sin(\alpha_{ref}) \\ &= P_{DC}\,/\cos(\alpha_{ref}) \cdot (\alpha - \alpha_{ref}) \cdot \sin(\alpha_{ref}) \\ &= P_{DC} \cdot (\alpha - \alpha_{ref}) \cdot \tan(\alpha_{ref}) \end{aligned} \tag{6}$$

Combining (6) and (4) yields the transfer function $H_I(s)$ from a current error I_{error} to an accelerating power P_{acc}.

$$\begin{aligned} H_I(s) &= P_{acc}(s)/I_{error}(s) \\ &= P_{DC} \cdot \tan(\alpha_{ref}) \cdot (\; K_P\,(1 + 1/(T_I\, s)\,) - \alpha_{ref}) \end{aligned} \tag{7}$$

In steady-state the integral term in the PI regulator of the CCA will meet α_{ref} so the transfer function to evaluate in a small-signal analysis is actually:

$$H_I(s) = P_{DC} \cdot \tan(\alpha_{ref}) \cdot K_P\,(1 + 1/(T_I\, s)\,) \tag{8}$$

Notice the factor $\tan(\alpha_{ref})$ in (8) from the linearization. This shows, that the amplification will be larger if the rectifier operates with increased firing angles. Also notice that the DC power P_{DC} is included in the expression; hence the amplification increases with the transmitted power. The real transfer function with-out idealising assumptions will of course be more complex than (8), but it will still expose the same basic dependence on P_{DC} and α_{ref}.

The integration term in (8) could lead to the conclusion that the risk of resonance increases more and more as the frequency decreases, but this is only true inasmuch as the preconditions are fullfilled. One of the preconditions was that the power plant controls could be ignored. In reality the governor, stabilizer, and exciter will start to counteract the accelerating torque when the frequency becomes sufficiently low; e.g. less than 5 Hz.

C. Nature of HVdc generated SSR

As can be seen from (8) any disturbance that causes a current error in the HVdc link returns an accelerating power to the generator rotor. It is also evident that the PI controller in the CCA means that lower frequencies have a larger impact on the accelerating power than higher frequencies.

Most disturbances have a wide frequency range and thus also includes frequencies in the SSR frequency range. Once a frequency is excited in the HVdc control system it provides an accelerating power to the generator rotor with the same frequency. If this frequency is a resonance frequency of the turbine shaft, the resonance is excited. Once excited the oscillation will be able to sustain itself, unless there is sufficient damping in other parts of the network.

As explained the network equivalent used to derive the transfer function (8) is very simple and does not include any resistances nor any other control devices. In reality the resistance in the AC network provides a more or less constant damping over the entire frequency range. This means that there is only a risk for SSR when the amplification by the CCA of a low-frequency disturbance is greater than the network damping.

D. SSR countermeasures

Since the problem is caused by the HVdc control system it is an obvious possibility to include an extra control function in the HVdc controls to counteract the low-frequency amplification of the CCA. This is called an SSDC (sub synchronous damping controller).

If an SSR oscillation is on-going it can be measured in the instantaneous deviation Δf of the network frequency from the fundamental frequency. An additional control signal in the HVdc control system can be calculated from this frequency deviation. SSDC's can be designed in many ways, but they will normally include band-pass filters to extract the specific

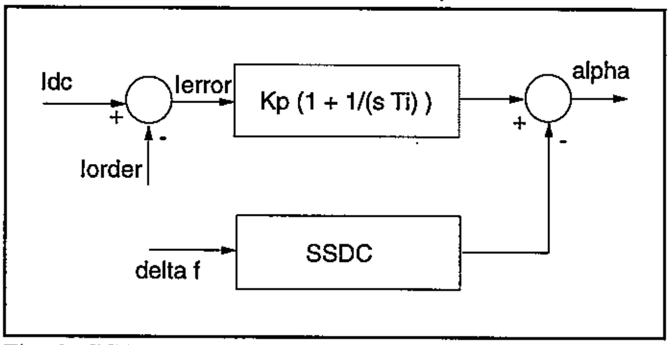

Fig. 3. CCA & sub-synchronous damping controller SSDC

critical frequencies in order only to affect the frequencies of interest.

The SSDC contribution can now be subtracted from the α-order of the CCA in the HVdc control system. Notice that the SSDC is included in the HVdc control system after the CCA, since it is the CCA itself which is the reason why there is a problem in the low frequency range. The CCA including the SSDC is depicted in fig. 3.

III. How to design an SSDC

The above example is very simple, and uses a transfer function from a current error to an accelerating power to demonstrate the cause of HVdc generated SSR. Once the nature of the SSR phenomenon has been understood it is easier to take effective countermeasures. In the following the steps in the design procedure of an SSDC is described.

A. Design of an SSR damping controller

The first step is to investigate whether there is a problem at all using the basic design of the HVdc controls; i.e. without an SSDC. This can be done by setting up a model of the worst case scenario for each generator under consideration in a simulation program that can determine transfer functions between an input and an output. As mentioned the worst case scenario is when a power plant feeds directly into a rectifier via a radial connection.

The model must include a good representation of all components (including controls) close to the generator and/or the converter station as well as in-between, and all known loss factors must be included. The turbine group in the power plant must be represented by one rotating mass.

A transfer function between a rotor speed deviation $\Delta\omega$ and the accelerating torque τ_{acc} must now be determined. For a closer description of this procedure see [1], and [5]. If this transfer function shows poor or negative damping close to a mechanical resonance of the turbine group then there is a problem, and it will be necessary to take some countermeasures and design an SSDC, that can introduce some additional damping in the critical frequency range(s). When this is done the procedure is repeated with the proposed SSDC in order to verify that it does indeed provide the necessary damping.

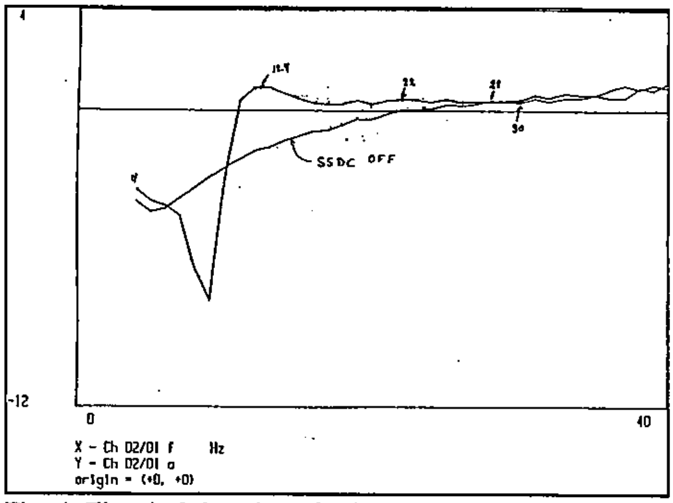

Fig. 4. Electrical damping of sub-synchronous frequencies.

As an example the transfer function $\tau_{acc}/\Delta\omega$ for the Asnæs power plant is shown in fig. 4 both with and with-out the SSDC in operation at the Kontek HVdc link. Radial operation is assumed with P_{DC} = 600 MW, and α_{ref} = 15°. The critical resonance frequencies have been marked on the plot. Notice that the SSDC actually introduces an increased negative damping for some frequencies; however this is unimportant since it is not in the vicinity of any critical mechanical frequencies.

B. Tuning of SSR Damping Controller

Now a good proposal for what the SSDC shall look like is available. However it has been developed using a one mass rotor model and with an open-loop transfer function - thus not allowing the resonance actually to be present - and with a program that determines transfer functions - thus implying a small signal analysis. Neither of these assumptions are fullfilled in reality, so it should be verified that the design is good enough also when these factors are taken into consideration.

This can be done using an analoque simulator or a digital simulation program where the same model is constructed; however this time with the transfer function loop closed in the generator. This time the turbine group must be represented with two rotating masses, where the inertias and the torsional spring constant between these masses are adjusted, so that the resonance frequency of the two mass system corresponds to one of the mechanical resonance frequencies of the real turbine group. Now the tuning and the verification of the SSDC can be performed for each resonance frequency by exciting the frequency - e.g. by applying and clearing a fault - and then monitor the decay of the SSR oscillation. This must be repeated with a new adjustment of the rotor masses and the spring constant for each resonance frequency.

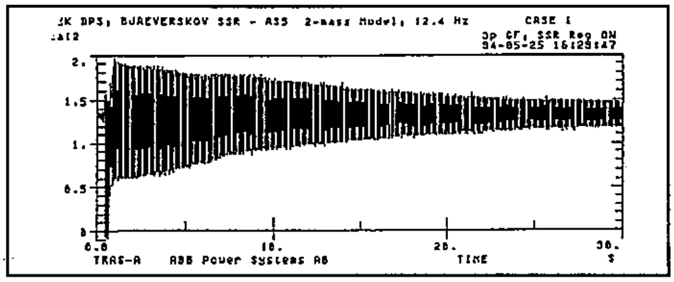

Fig. 5. Oscillogram of mode damping for mode 1.

In fig. 5 an oscillogram of the decay of the most critical frequency at the Asnæs power plant is shown.

IV. SSDC TEST PROCEDURE

After the design and tuning of the SSDC the next step is to perform a full-scale test while commissioning the HVdc link. For the Kontek link this was performed in a two-step procedure; first in a normal network configuration in which there ought not to be any problems, and, - once that had been verified, in the worst case situation. The test procedure is described first and then the results afterwards.

A. Test in normal network configuration

The purpose of the test was to verify that the modal damping for all resonance frequencies is positive.

At first the converter was blocked with a load of 70 MW. This did excite all frequencies simultaneously with a sufficiently high amplitude to allow a measurement of the damping for all modes. At the same time it was verified that the measured resonance frequencies correspond to the theoretically calculated frequencies.

After this each mode was separately excited using the HVdc link. The power order of the HVdc was 70 MW, and the production at the power plant was 520 MW. The current order was modulated with each resonance frequency starting with the highest frequency, and the amplitude of the SSR oscillation in the power plant was measured. The amplitude of the modulation was increased until the amplitude of the SSR oscillation had reached 40-80 % of the safety limit specified by the turbine manufacturer. At this instant the modulation was interrupted, and the mode damping was measured respectively with and with-out the SSDC in action. This test was performed twice for each frequency.

It should be noticed that the SSDC is an integrated part of the HVdc control system. It is only possible to disable it by changing the code in the control system. It is <u>not</u> possible for the operator to disable the SSDC in any way.

It should be emphasized that there is a very big risk involved when deliberately exciting SSR oscillation modes directly at the machine. For safety reasons a direct telephone connection was established between the converter station control room and the power plant during these tests. In this way it was possible to order an interruption of the modulation of the HVdc immediately, in case the SSR oscillations became higher than the safety limit. And in case this procedure did not work or was not enough to damp an on-going SSR oscillation preparations had been made in the power plant to trip the unit immediately simply by pressing a button.

B. Test in weak network with radial connection

In this case the configuration in fig. 1 was used except that there was a transformer connecting the power plant to the rest of the AC network. This was necessary since it is not possible to control the power from a power plant so accurately that it exactly meets the ordered power of the HVdc. It should be noticed that this difference means that the short circuit capacity at the Asnæs power plant was significantly higher than it would be in the real worst case scenario with a true radial operation; hence the risk of SSR is smaller [1].

The same tests were performed, however in this situation both the HVdc power order and the power plant production was 450 MW.

Furthermore an additional test was performed for all modes, where the HVdc was operating with increased firing angles as an absolute worst case. This test was only performed with the SSDC in operation, since it was expected that the damping would be very low or maybe even negative if the SSDC was disabled in this situation.

V. RESULTS

A. Measured results

The mode damping of all modes was measured in all the tests, and the values are within the limits indicated below.

Mode 1 (12.49 Hz): 0.063- 0.179 s^{-1} *
Mode 2 (22.10 Hz): 0.101 - 0.167 s^{-1}
Mode 3 (27.60 Hz): 0.195 - 0.338 s^{-1}
Mode 4 (30.10 Hz): 0.113 - 0.149 s^{-1}

*: If the radial operation tests with increased firing angles respectively with the SSDC disabled are disregarded the mode 1 dampings are within the range 0.109 - 0.179 s^{-1}.

The damping is considered to be good if it is more than 0.1 s^{-1}. Thus the above figures show that the damping is good for all modes in all situations except in radial operation for mode 1 when the SSDC is disabled or when the rectifier is operating with increased firing angles. Even in these situations the damping is still positive.

As mentioned it is not possible to disable the SSDC, so there is only a potentially hazardous situation in radial operation and with increased firing angles. This is considered to be a very rare form of operation in the east danish network, so it was decided <u>not</u> to change the SSDC, so that it would provide damping also in this situation. Instead it was decided to make an operator instruction that forbids the use of manually increased firing angles and that describes which HVdc control functions to disable in radial operation in order to prohibit an unintentional automatic increase of firing angles.

B. Comparison between calculated and measured results

It is not easy to make a meaningfull comparison, since there is a limited amount of measured data, since the calculations and the simulations were performe in different ways, and since the measurements were performed with network operating conditions that were not examined during the calculations. However an attempt will be made anyhow.

The following damping constants were measured in the tests with radial operation, normal firing angles, a DC power of 450 MW, and with a 400/132 kV-transformer connected at the power plant.

Mode no. & frequency:	With SSDC:	With-out SSDC:
Mode 1 (12.49 Hz)	0.114 s^{-1}	0.082 s^{-1}
Mode 2 (22.10 Hz)	0.133 s^{-1}	0.137 s^{-1}
Mode 3 (27.60 Hz)	0.226 s^{-1}	0.209 s^{-1}
Mode 4 (30.10 Hz)	0.133 s^{-1}	0.120 s^{-1}

These damping constants can be compared with the transfer functions in fig. 4. Obviously the calculated results are more pessimistic than the measured, since the calculated results expose negative damping for the low frequencies with the SSDC disabled. This was not the case in the same situation during the measurements, where there was positive damping in all cases. However this could be expected, since the transformer at the power plant increases the short circuit capacity and thereby also the damping.

The only thing that can be definitely concluded is that the SSDC improves the system damping in simulations as well as in measurements. Further more it is likely that the damping would be negative - or at least very low - for the lowest resonance frequency with the SSDC disabled if the transformer at the power plant was disconnected. This is concluded since the damping already is very low even with this transformer.

VI. MEASURING TECHNIQUE

A. Measuring technique in the SSR test

The measured signals consisted of 3 measurements of the speed deviation from synchronous speed taken at the locations (Mess-stelle 1,2, and 3) indicated in fig. 6. The mode shapes of the various resonance frequencies are also shown in fig. 6.

The first speed measurement was made by a transducer sensing the position of a gear tooth-wheel, and the two last measurements were made by transducers sensing the position of aluminium pulse strips on the turbine shaft. A fourth signal was calculated from the two last measured signal by

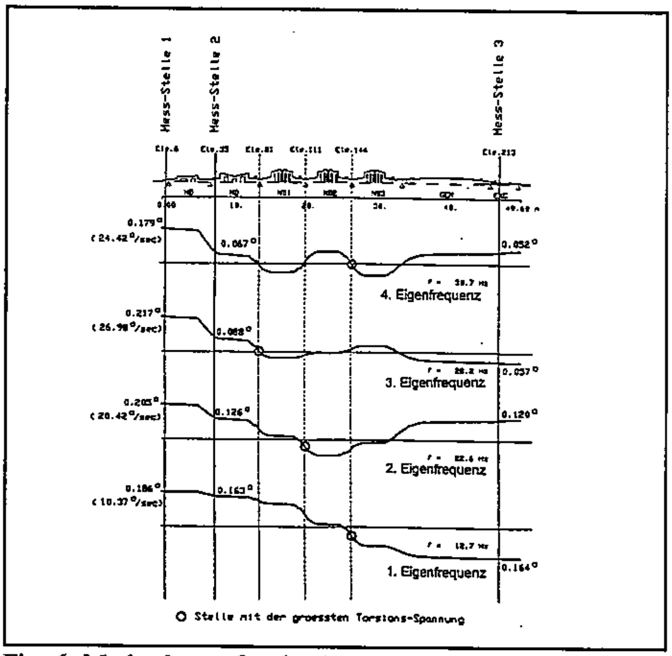

Fig. 6. Mode shapes for the Asnæs power plant unit 5

integrating the difference between measurements 2 and 3; in this way the angle deviation from the steady-state angle was obtained.

These analoque signals were processed further in a PC-based data aquisition system using a sample frequency of 250 Hz. To avoid aliasing the signals were low-pass filtered before the A/D conversion.

The signals were recorded for later processing in the PC. The most important part of this postprocessing was a band-pass filtering to extract each of the modal frequencies followed by a modal damping analysis of the filtered signals. The exponential damping was then calculated in a selected time interval. As an example see fig. 7 where the modal damping for mode 1 (12.49 Hz) is shown for radial operation with, respectively without the SSDC. The signal used is signal 1 (the measured speed deviation at the tooth wheel).

B. Experimental measuring technique set-up.

It was decided to try whether or not it is possible to measure SSR in some of the electric quantities (stator current, stator voltages) that are measured anyhow in a power plant. Of course the SSR frequencies are present also in the stator currents and voltages if there is an SSR oscillation ongoing, but the question is whether or not it is so clearly present that it is possible to detect it. Therefore it was decide to make an attempt to measure SSR oscillations in the stator currents during the SSR test.

First of all it should be made clear, that if the resonance frequency is f_{res} then it should not be expected to find this frequency in the measured currents. On the contrary one must expect to find the slip frequencies $f_{net} \pm f_{res}$; e.g. for a

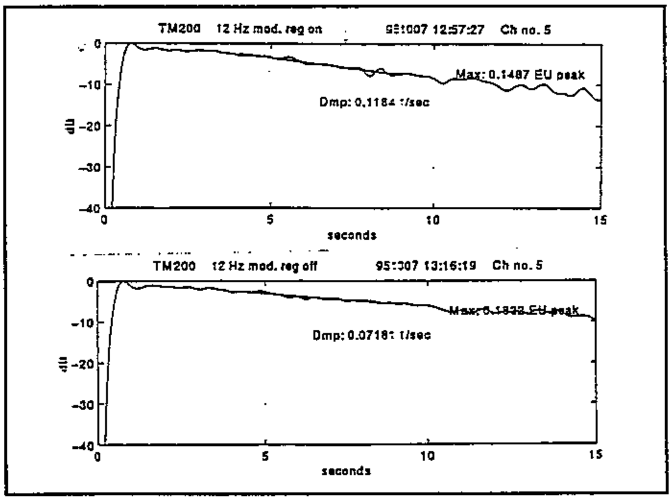

Fig. 7. Modal damping for mode 1 (12.49 Hz)

resonance frequency of 12.5 Hz in a net with a 50 Hz fundamental frequency it must be expected to see the frequencies 37.5 Hz and 62.5 Hz.

The set-up was quite simple. The instataneous values of the stator currents were sampled with 200 Hz and recorded on the harddisk of a PC using a standard A/D conversion card. The measurements were triggered manually whenever an SSR oscillation was on-going. This was known from the SSR test. The recorded data were processed later.

Two measured events were postprocessed; one where mode 4 (30.10 Hz) and one where mode 1 (12.49 Hz) was excited. The results were partly positive. It was not possible to detect the frequencies 19.90 Hz and 80.10 Hz in the spectrum of the first measured signal. On the other hand it was clearly possible to detect peaks in the spectrum of the second measured signal around the frequencies 37.5 and 62.5 Hz; see fig. 8. The spectrum in fig. 8 is the average value of a large number of spectres each taken over a window of 128 samples. The spectrum has distinct peaks at the two slip frequencies corresponding to mode 1. Hence it is possible to detect this SSR frequency in the stator currents.

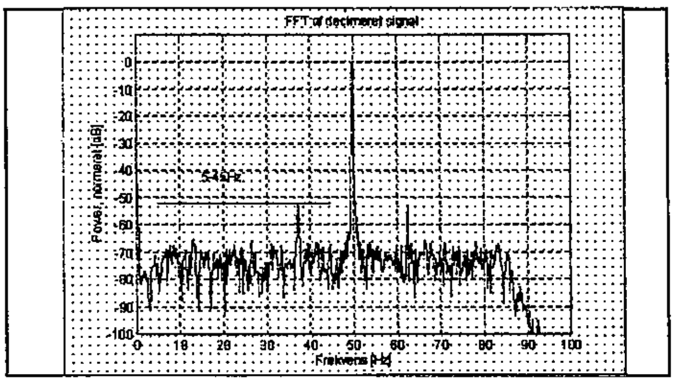

Fig. 8. Spectrum of phase A current with SSR mode 1

The only conclusion that can be drawn from the results is that it indeed is possible to detect at least some SSR frequencies in the stator currents. Since the results were encouraging in this aspect further investigations are currently being performed in the form of a student graduation work from a technical university.

VII. CLOSING REMARKS

HVdc generated SSR is a serious hazard that must be taken into consideration whenever planning and commissioning an HVdc converter station in the electrical vicinity of a power plant (or vice versa). However once the problem has been recognized it is straight-forward to take countermeasures. If this is done at an early time in the planning stage of the HVdc link the marginal cost will be very low. The SSDC in the HVdc control system - as well as the test of the SSDC - will just be a small part of the total HVdc delivery from the supplier.

If it is desired to obtain a quick indication whether or not SSR is present at an existing power plant unit this can be done by measuring the sub-synchronous spectrum of the stator currents. If the generator rotor takes part in a specific SSR mode the slip frequencies of this mode will very likely be present also in the stator currents.

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