SUB SYNCHRONOUS OSCILLATIONS

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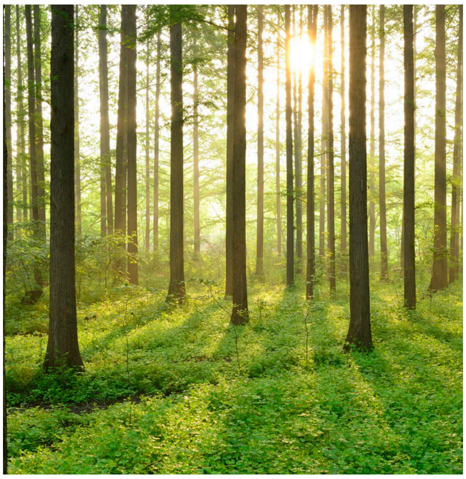

GRID INTERFERENCE ON NUCLEAR POWER PLANT OPERATIONS

Energiforsk

Sub Synchronous Oscillations

Synthesis of seminar held on November 24, 2016

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Foreword

Subsynchronous resonance is not encountered very often, but if it occurs it is a very serious problem and can cause severe damage in a power station. Specific preconditions are required – a power plant with an extensive turbine-generator string located near a long power transmission line with series capacitors. Given the severe consequences, power plants that risk subsynchronous resonance are equipped with suitable protection. In the Nordic system, two nuclear power plants risk problems caused by subsynchronous resonance - Forsmark 3 and possibly Olkiluoto 3.

A seminar was arranged on November 24, 2016, within Energiforsk R&D program Grid Interference on Nuclear power plant Operations, GINO. At the seminar, different types of subsynchronous oscillations/resonances were described and methods for protection against, and mitigation of, the phenomena was discussed. The seminar was planned by Per Lamell at Forsmarks Kraftgrupp. Presentations from the seminar are published on www.energiforsk.se. This report is a synthesis of the seminar, compiled by Göran Lindahl, senior researcher at STRI.

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Monika Adsten, Energiforsk

Sammanfattning

Resonans mellan synkrona elektriska generatorer och det elektriska transmissionsnätet kan uppstå för andra frekvenser än grundfrekvensen, 50 eller 60 Hz. Resonanser i det elektriska nätet kan uppstå när nätet innehåller seriekondensatorer och dessa resonanser kan vara av så kallad subsynkron natur och ha sin orsak både i serie- och parallellresonans.

Om sådana subsynkrona resonanser i nätet sammanfaller med mekaniska torsionsfrekvenser hos axelsträngen hos turbin-generatorn så kan interaktion mellan dessa system uppstå vilket normalt brukar benämnas subsynkron resonans (eng. SSR). Om den elektriska dämpningen för en viss frekvens i nät är otillräcklig eller negativ i förhållande till den mekaniska dämpningen i axelsträngen kan detta leda till farliga påkänningar eller t.o.m. haveri av axelsträngen. Liknande fenomen kan även uppstå som resultat av samverkan mellan kontrollsystem för t.ex. HVDC omriktare och turbin-generatorer och ger en subsynkron interaktion mellan nätet och axelsträngen (eng. SSTI).

Vid seminariet behandlades olika aspekter subsynkrona oscillationer såsom metoder för analys och beräkningar av dessa samt inkluderande flera exempel. Sådana presentationer gavs både av systemoperatörer och av bolag från den tillverkande industrin. Metoder för att motverka oscillationer både vad gäller serie kompensering och HVDC gavs bolag som tillverkar sådan utrustning. Vidare gavs av tillverkare presentationer som beskrev vilka mätprinciper som används samt ny filterteknik i syfte att kunna övervaka och skydda utrustning om SSR uppstår. Från nätoperatörens sida rapporterades om goda driftserfarenheter av nya skydd för SSR.

Syftet med seminariet var att samla folk från kärnkraftsindustrin, övervakande myndigheter, nätoperatörer, universitet, tillverkande industri, konsulter etc. för att diskutera och sprida kunskap om resonansfenomen. Sådana fenomen som kan drabba t.ex. stora ångdrivna turbin-generatorer som t.ex. används i finska och svenska kärnkraftverk.

Seminariet hölls på engelska.

Summary

Resonance between electrical synchronous machines and the electrical grid may occur for frequencies other than the fundamental frequency (50 or 60Hz). Natural resonances in the electrical grid incorporating series capacitors can occur for subsynchronous frequencies and be both of series or parallel resonance nature.

Should the subsynchronous resonance frequencies of the network coincide with any of the mechanical frequencies of the turbine-generator shaft torsional interaction may appear which is referred to as Sub Synchronous Resonance (SSR). If the electrical damping for a specific frequency in the network is insufficient or negative in comparison to mechanical damping, it may lead to mechanical stresses or even failure of the shaft system. Similar phenomena can occur also between a control system of for instance a HVDC converter and the turbine generators, this is often referred to as Sub Synchronous Torsional Interaction (SSTI).

At the seminar, different aspects of subsynchronous oscillations such as methods of analysis calculations was presented by transmission system operators (TSOs) and from the manufacturing industry together with many examples. Mitigation methods were presented by manufacturer of series compensation and by manufacturer of HVDC systems. Demonstrations of measuring principles and new filtering techniques for monitoring of and protection against SSR were given by manufacturer of protection. Good operation experience of new SSR protection was reported from the TSO side.

The purpose of the seminar was to gather people from the nuclear industry, nuclear authorities, transmission network operators, researchers from universities, equipment manufacturers, consultants etc. to discuss and to spread knowledge and experience about different kinds of resonance phenomena. Such phenomena could affect large steam driven turbine-generators sets as those utilized by the nuclear power plants in Finland and Sweden.

List of content

1 Scope

The seminar was held at Energiforsk office 2016-11-24 and was open to different stakeholders such as nuclear industry, TSOs, power companies, manufacturing industry, universities and researchers, consultants etc. Participants and lecturers from both Finland and Sweden were present at the seminar.

The seminar was quite broad in its approach dealing with various aspects of subsynchronous oscillations (SSO) as for example methods of calculation and analysis, measurement, mitigation and protection. The seminar focused mainly on SSO that could lead to torsional interactions with turbine-generators like those in nuclear power plants. Several examples of calculations and measurements were reported.

2 Summary of presentations

Below follow summaries of the different presentations held at the seminar.

2.1 WELCOME BY ENERGIFORSK

The welcome to the seminar was given by **Mrs. Monica Adsten**. A brief introduction to Energiforsk as organisation in general was given and with its mission to create benefits in form of reports, seminars, guidelines, education etc. An overview of the six areas of activities for the nuclear portfolio was presented. The area Grid Interference on Nuclear Operations (GINO) is the area under which the SSR seminar belongs. For the GINO part the vision, the focus area and the activities were presented. The organisations participating in the steering group were also presented.

2.2 INTRODUCTION BY FORSMARKS KRAFTGRUPP

The introduction to the seminar was held by **Mr Per Lamell** who also served as moderator during the seminar. The background, the interest for and the scope of the seminar was presented. The seminar forms a part of the strategy plan for GINO (Grid Interference on nuclear Power plant Operations). The expected outcome of the seminar is a description of the phenomenon and what information is needed to make SSR calculations.

The presentation gave a motive for the need to look at different kinds of resonance such as series compensation, HVDC, static VAR which motivates the different kinds of presentation held during the seminar. Definitions of SSR (Sub Synchronous Resonance) and SSO (Sub Synchronous Oscillations) was given.

SSR was in principle an unknown problem at the first of the incidents in the Mohave (1970) plant in New Mexico, US but it was not until the second incident in 1971 that it was figured out what was the cause of the damages (SSR).

The principal arrangement of the original SSR protection at Forsmark 3 was presented, it had beside the protection function also a torsional monitoring system connected to the shaft.

Example of a turbine string with mass moment of inertias and spring constants was given (damping constants is however more difficult to obtain). Also natural torsional frequencies (sub and supersynchronous) were presented. For Forsmark 1/2 the damping at the torsional frequencies is always positive. For Forsmark 3 the damping is dependent on the grid configuration.

2.3 SUBSYNCHRONOUS RESONANCE AND TORSIONAL INTERACTION – BACKGROUND AND PHYSISCAL UNDERSTANDING

The presentation was made **Mr Kenneth Walve**. Mr Walve described how the knowledge of the phenomenon was built up.

The approach to the subject was developed based on physical understanding and to get the feeling what was the real problem and to get an understanding of the most critical parameters affecting it. Distinguishing between the electrical, the mechanical and the interaction part between them was an important part of the task. Some early events were mentioned as the "famous" Mohave incidents and failure (1970/1971), field tests in Mexico (real time torsional measurements) and an incident of SSR in Sweden December 27, 1983.

Three areas of SSR analysis were brought up:

1. Induction Generator effect. A pure electrical phenomena, where the negative resistance (at SSR frequency) becomes more negative than the positive resistance of the grid (not considered a problem in Swedish grid)
2. Shaft Torque Amplification. This is due to switching sequences (such fault, fault clearing and auto-reclosing actions) and can give high instantaneous torques which can further be amplified by resonances in the grid (not subject to further investigation in the SSR work).
3. Torsional interaction. If torsional oscillation of the mechanical shaft occurs, subsynchronous frequencies will appear and if these subsynchronous frequencies coincide with electrical resonance frequencies of the grid then oscillations may be amplified, which can cause damage to the shaft.

Mechanical damping of turbine is likely to be caused essentially by the steam flow. There is a damping dependence of the steam flow, at no or low load the damping is low, much lower than at full load. Damping at full load can typically be a factor 3-5 higher than at no-load. The damping time constants can be in the order of a few seconds to half a minute.

A model of the shaft system can be set up with lumped masses representing the different masses (HP- and LP-turbines, the generator and exciter), the spring constants of the shafts connecting the masses and damping constants of the masses. The relation of the constants forms a differential equation with respect to the torsional angle. At the beginning of examining the problem a working group was formed with representatives from ASEA, STAL Laval and Vattenfall which helped to understand the physiscs of the problem and to derive the above mentioned constants. However, mechanical damping is very difficult to calculate and tests and backward calculation were used for damping estimation.

On the electrical side the inductive and capacitive grid elements can either form a series resonance circuit or a parallel resonance circuit.

At oscillations the generator will be exposed to frequencies both below (subsynchronous) and above (supersynchronous) the nominal frequency. Fluxes at these frequencies will induce voltages with corresponding frequencies that will result in currents in the grid. These currents are given by the impedance of the grid (including the generator) for the corresponding frequencies. The sub and supersynchronous currents will interact with the sub and supersynchronous fluxes generating torques that can either damp or amplify the mechanical oscillations. The total torsional damping comes from subsynchronous electrical damping, the supersynchronous electrical damping and the mechanical damping.

Frequency scanning of the network is important and it is important to scan the complete frequency range. The electrical damping (sub and super) can often presented in a form related to the series compensation degree of a line or as an area for two series compensated lines. This may lead "forbidden" area levels with respect to compensation levels.

High resistance of the network (degraded network) in combination with low load on the turbine (i.e. start-up) can cause conditions that could give non-damped torsional interaction.

The build up of the knowledge resulted in the Vattenfall report "A Methode of Synchronous Resonance" which has been made available to seminar auditors on Energiforsks homepage (www.energiforsk.se)

2.4 SSR ANALYSIS AND DESIGN OF SSR PROTECTION IN SWEDEN

The SSR Analysis and Design of SSR Protection presentation was given by **Mr Per-Olof Lindström.**

The presentation touched the three different SSR phenomena; Torsional Interaction, Induction Generator Effect and Shaft Torque Applification. Mainly the first of these three phenomena was treated in the presentation. The method used by Svenska Kraftnät for analysis is based on the one developed by Vattenfall. In the analysis the mechanical and electrical systems are treated separately with the synchronous generator acting as the link between them. The torsional interaction acts like in a "circle relation" where the torsional oscillation induces a voltage with frequency $f\text{-}f_m$ that leads to corresponding currents which magnitude and phase is given by the network impedances. The current (with frequency $f\text{-}f_m$) which flows in the stator creates a torque (with frequency f_m). The torque depending on its phase will either amplify of damp the initial oscillation. The number of mechanical torsional frequencies is n-1 the number of lumped masses (n) of the shaft train. According to presentation simplified models will give about the same mode frequencies as those given by manufacturer based on detailed calculations. Calculation with lumped model will give the mode shapes for the corresponding mechanical frequencies. Each mode will have its own shape showing in principal which of the masses that are mostly involved in the torsional oscillation and it will indicate which shaft section is the most stressed one. The mode do only indicate the shape not the absolute magnitude, but the magnitude is normalised for the mass that has the largest amplitude (set to +/-1). To be able to interact with the network, the mass representing the generator rotor must not have zero amplitude otherwise it cannot cause any electrical interference with the grid.

The development of the analysis tools used since 1970´s up to today was presented with examples. The analysis is based on the tool PSS/E with complementary programs. Study of one generator at time with frequency scanning of the network (including the generator) is used and executed for several contingencies. The result is damping and line currents. It was demonstrated that the damping decreases for higher rated apperent power of a generator. Examples from studies were shown giving both damping and current with respect to the torsional frequencies identified without and with series capacitors by-passed. Bypassing of the series capacitor with the highest SSR current increases the damping. An example with a wide variety of contingencies was presented showing that some gave very negative damping, but did not coincide with mechanical frequencies.

Philosophy of the protection system for SSR was presented with primary protection installed at Stackbo and Ängsberg and with secondary protection at Forsmark 3. The primary line protections bypass the series capacitor and the protection at Forsmarks trips the unit. Voltage is used for measurement in Forsmark and current is used for measurement at the series compensated lines. The protections are using an inverse time characteristic.

Some questions from the auditors regarding how loads and other generators was treated in the calculation. It appeared as they were represented by their short circuit equivalents.

2.5 EXPERIENCES FROM SSTI-STUDIES IN HVDC PROJECTS

The presentation was given by **Mr. Adil Abdalrahman**. The presentation was divided into five sections, Approach for SSTI, Screening study, Detailed study, Examples from HVDC projects and Ferroresonance. Some definitions of abbreviations was given like SSO (Sub Synchronous Oscillations), SSR (Sub Synchronous Resonance) interaction of passive elements as series compensated lines and shaft system, SSTI (Sub Synchronous Torsional Interaction) interaction of active elements/power system control and shaft system (as HVDC, SVC/STATCOM, Governors, Power System Stabilisers), SSCI (Sub Synchronous Control Interaction) interaction of power electronic control systems of HVDC or wind turbines (DFIG) and series compensated lines (not shaft system related). Principal figures of SSTI for both line commutated and voltage source converter HVDC were shown. A schematic figure of stresses on turbine shaft was presented.

The approach for SSTI study is first to make a screening study using a defined UIF (Unit Interaction Factor) for which a relation was defined in the presentation. If the UIF is low (less than 0.1) the risk for SSTI is low too. The UIF increases with a more radial network and with a higher contingency order. An example of a large network topology studied including several generating units was shown and results of UIF factors for many contingencies were presented. For cases with high UIF detailed studies are conducted where the damping torque is analysed. In principal the mechanical damping torque is always positive but the electrical damping may become negative for certain frequencies. If the sum of mechanical and electrical damping is bigger than zero stable operation is present. Mechanical damping tends to be higher for torsional modes near synchronous frequency. In the analysis if electrical damping of the HVDC is as good as the case without HVDC the torsional stability is secured. Addition of a SSDC (Sub Synchronous Damping Control) can be used if analysis shows damping is insufficient.

Several examples of studies including cases with poor or negative damping was presented and where mitigation in form of SSDC was introduced to increase damping. Examples are showing both the increased damping as a function of frequency as well as time domain simulation simulations showing the difference with and without SSDC. For one example (Fenno-Skan 2) tests at site were also used initiating SSTI, the conclusion was that link did not deteriorate the damping. An examples of a study case with a back-to-back HVDC converter connected to series compensated lines showed how SSCI is assessed. The study showed result both from impedance scanning and from time domain simulations.

Further an example for ferroresonance was shown including a system with series compensated lines. The example showed, with the aid of time domain simulations, following a fault on the AC side the effect of ferroresonance, for instance in form of a varying power on the DC side. Introduction of a ferroresonance damping controller to the HVDC link showed how this resonance could be mitigated.

Some other examples from HVDC projects where SSDC controls have been used were also shown during the presentation (however these examples are not included in the presentation material gathered from the seminar).

2.6 TCSC INTRODUCTION AND ITS CAPABILITY ON SSR MITIGATION

The presentation was held by **Mr Hector Latorre**. An introduction was given showing a typical configuration of a TCSC (Thyristor Controlled Series Capacitor) with all the components forming the unit. Different areas where the TCSC can be used, as power oscillation damping, transient stability voltage control etc. were presented but the focus in the presentation was on SSR mitigation. The bases for dimensioning the different components with the TCSC were explained. Principal equations for the currents through the capacitor and the reactor were presented. The modes "blocked mode" (capacitor only) and the boost mode was given (the thyristor valve current and line current shifted 180 degres). The extra current from the thyristor controlled reactor branch boosts the voltage over the capacitor increasing its voltage slightly, a boosting factor can be defined as $k_B = \hat{U}_{c1}/\hat{U}_{c0}$. The higher firing angle the higher voltage over the capacitor, and an increase in apparent capacitive impedance, up to a certain angle where the complete unit turns into an inductive impedance. A boosting factor of up to 3 times can be used. For SSR mitigation the boosting factor was reported to be typically around 1.2.

When the thyristor is conducting a voltage reversal occurs over the capacitor which coincides with peak of the current through the thyristor. The apparent impedance for the SSR frequency can then be controlled. Compared to a fixed series capacitor the voltage over capacitor can be kept fairly constant which helps to mitigate SSR. Different control patterns of the valve for different SSR frequencies were shown in the presentation. It was shown from a mitigation example that the TCSC gave the same electrical damping as no series compensation with respect to torsional frequencies. Examples from RTDS test were shown comparing fixed series capacitors with TCSC verifying the electrical damping. If TCSC is combined with a fixed series capacitor (split arrangement) on a line it was shown that the TCSC has the capability to move the resonance point and may thereby still be effective in mitigating SSR.

2.7 SSR INTRODUCTION AND THEORETICAL SSR AMPLITUDES

The presentation was given by **Mr Stefan Roxenborg**. The work started in 2012 together with Svenska Krafnät, Forsmarks Kraftgrupp to record SSR events both at Forsmark 3 and at Ängsberg and Stackbo substations. The purpose was to replace an existing old analogue SSR protection. This was considered necessary due to the upgrade of Forsmark 3 as this meant new equipment which would likely change the SSR mode frequencies. The cause of SSR can be the turbine, the excitation or the series capacitor. The frequency of the SSR is related to the fundamental frequency and mechanical frequency through the relation $f_{SSR}=f_{Fundamental}+/-f_{Mechanical}$.
It is a challenge to detect the SSR frequencies using the measured current and voltages as their amplitudes are very small compared to the fundamental frequency component. For instance the current can be in the order of 0.1% to a few percent of the fundamental current. For this purpose extremely good filtering was deemed as necessary.

The SSR currents depend on the power system impedance at SSR frequencies while SSR voltages are proportional to the amplitude of axis. It was also stated that SSR voltages are proportional to SSR frequencies which was found not to be the case for SSR currents.

The theoretical relationship for the voltage induced in the stator in relation to mechanical resonance angular velocity deviation was presented and from this a relation of amplitude dependence of the super and subsynchronous voltages was given. This relation gives an effective criterion to disclose disturbances that are not of SSR character as both sub- and supersynchronous frequencies have to exist at the occurrence of SSR. In addition amplitudes have to be approximately in relation to each other when SSR is present.

2.8 SSR FIELD OBSERVATIONS

The presentation was held by **Prof. Tord Bengtsson.** The work begun with a "starting to observe" approach by installing IEDs in Stackbo and Forsmark 3 in 2012 and analysis was made off line. Example of SSR events were presented with disturbance recordings and with spectral movies from both Forsmark and Stackbo. Three resonance frequencies pairs were observed (sub and supersynchronous). It was found necessary to log SSR activity continuously.
Upgrades of equipment was made in 2013 shifting location to Ängsberg and also with a new filter included in the IEDs. Increased logging capabilities (PCs) were added. Examples of SSR from July-September were shown at the presentation with several SSR events having duration times of several minutes up to half an hour. For one event in 2013 the old SSR protection tripped but no initiating cause was found in the loggings but there was a true resonance (31-31.5 Hz) present.

Introduction to the High Precision AC filter was given which is similar to DFT filter however with higher precision. The filter was developed initially for other measuring applications. It can be used for any frequency and does not need synchronised samples, it returns both peak and phase. The principle is also used for some other protection functions within ABB (generator) protection. The precision comes from fairly long recording times and filtering length is very important for results.

The conclusions were that SSR can be both initiated by triggered events and then decays quite fast but can also appear without any triggered events and may then have duration of minutes or even hours. It appears as SSR seen at the generator is more informative and that voltage is better used there. The filter can give a sensitivity of 0.1% in relation to the fundamental component

Some questions were raised by the auditors:

Can you observe frequencies for different generators or do you need to know them?
Answer: Yes, by inspecting spectra we can find which SSR frequencies that are active.

Could something be said regarding amplitudes for sudden trigged SSR versus those without any triggering event and with long duration?
Answer: It is hard to say that amplitudes are different.

Will the noise be worse for longer filter lengths?
Answer: No, it will decrease and more peaks may be seen if filter length is increased

2.9 DESIGN OF NUMERICAL SSR PROTECTIONS USING ABB 670 SERIES IEDS

The presentation was given by **Dr. Zoran Gajić**. A brief overview of the portfolio of grid automations products, where the IEDs are one of many components, was shown. One of the bases for the new SSR protection is that there was no other commercial product available and that the knowhow and the equipment were old.

The 670 series have in principal the same filter (for the purposeof other protections). Detecting a few amps when the rated current is about 40 kA (Forsmark 3) is very difficult.

The SSR protection is a customised special protection within the IED 670 series. The SMAI HPAC filter for SSR gives phasors (amplitude and angle) for specific frequencies. Standard voltage transformers (VT) and current transformers (CT) are used. Due to the very high rated current of the generator (Forsmark 3) and the requirement of detecting low values of SSR current, voltage is a more suitable measuring quantity at the generator. The dynamic range of the voltage is lower compared to the current which makes the voltage at the generator to be the better choice.
3-phase quantities are used and there is no need for any filter tuning. Filter time is 1 s (a combination from requirements of precision and of speed) and the output is updated each 256 ms. The output is phasors (real and imaginary part) together with information of frequency. If there is no SSR activity the filter returns 0 in amplitude and -1 in frequency. The output is then sent to standard protection functions for overcurrent and overvoltage. The functions have an Inverse Definite Minimum Time (IDMT) delay which offers a flexible setting. It was reported that the setting of the IDMT function was configured to mimic the same inverse characteristic as the old SSR protection. Both the super and subsynchronous voltage in combination are used for tripping at Forsmark 3.

For the SSR protection on the lines subsynchronous current is used as measuring criterion.

In the SSR equipment installed at Forsmark 3 there is also possibilities for logging SSR data over a longer period of time (year) which makes it possible to follow trends.

2.10 EXPERIENCE FROM THE SWEDISH TSO IN RUNNING THE NEW SSR PROTECTION

The material was compiled by **Mr Håkan Eriksson** but the presentation was held by **Mr Per-Olof Lindström.** The presentation showed that the new protection is installed at the line ends for the three series compensated lines connected in Ängsberg (2-lines) and Stackbo (1-line). The former (old) protection was situated at the capacitor banks. The reason why the protections are now situated at the line end was told to be because 3-phase measurement (current and voltage) is necessary and that 3-phase measuring transformers are not available at the capacitors banks. The protections act through telecommunication for by-passing the series capacitors (cascade tripping is utilised in Vittersjö, tripping first one of the banks and if the conditions remain the second bank).

The protection terminal has 6 filters but only two are used for protection purpose using current as measurement signal. The protections are set for two specific SSR frequencies with certain frequency band (32.9 +/- 1.5 Hz and 37.5 +/- 1.5 Hz) and are using an extremely inverse time function for tripping. Hence, tripping time is long for moderate SSR current above the setting value and short for high values above the setting value. The remaining 4 filters are used recording purposes and set to record currents in both sub- and super-synchronous area and for specific subsynchronous mode for voltage.

A number of unwanted by-pass operations occurred initially due to transients but after modifications of the new protection operating experience has been very good with no unwanted bypass operations. The old protections have initiated several of bypass operations (thousand) during their operation period (approx. 30 years).

Example of a network transient causing disturbance recording start was shown

2.11 EXPERIENCE FROM THE FINNISH TSO

The presentation was given by **Mr Tuomas Rauhala**. The presentation described four cases: 1) Planning studies to address HVDC SSTI for five torsional oscillation modes, 2) HVDC SSTI and SSO protection co-ordination, 3) Monitoring of total torsional damping using PMUs and 4) SSR torque amplification in meshed series compensated network. A brief description of the Finnish transmissions system with its placement of series compensation and HVDC links in relation to large thermal units was given. Due to the network topology, HVDC SSTI has been more of interest than SSR against series compensated lines.

For case 1) may conditions had to be examined due to several changes, amongst them Fenno-Skan 2 commisioning, upgrade of Fenno-Skan1, uprate of Olkilouto 1&2, planned commissioning of Olkilouto 3 and AC network reinforcements. Many uncertainties to deal with.
For case 2) three questions was to be answered: Effect of parallel AC network on selectivity of SSO protection (based on local frequency measurement), Effect of HVDC system on selectivity SSO protection (based on local frequency measurement) and a special case with two closely situated torsional modes associated with different units. Figures were given showing the effect of HVDC on local frequency measurement for the different generators. The conclusion was that it was not possible to implement a selective HVDC SSO protection (to high risk of losing both HVDC poles and/or worsening the conditions).
For case 3) various figures of PMU recordings of post disturbance recordings were presented. Levels of oscillation and estimated damping as a result of PMU measurement over a two year period were shown. Recorded modes from PMUs agreed well with torsional modes for Olkilouto 1&2.
For case 4) the IEEE benchmark model is considered a good method for validation of SSR TI but is not suitable for large meshed networks with series compensation and planning issues are not addressed. A new benchmark model for 10000+ cases are needed for analysis and then from the outcome of that model a fewer number of cases should be picked for EMT studies of torque amplification. Only the first part of this study was conducted.

2.12 DISCUSSION

From one of the previous presentation a question was raised: What is the torsional withstand capability of the turbines?

An example of a withstand curve was shown by Forsmarks Kraftgrupp for a Low Pressure turbine. The curve showed the superimposed torque versus number of cycles (torsional) in a log-log scale. The outcome from the curve, which has an inverse characteristic, shows that the higher the torques the fewer number of cycles it can withstand. At certain limit, 1.0 p.u. torque and below, the number of cycles is unlimited and for a high limit about 10 p.u. and above, damage will occur immediately.

3 Conclusions from seminar

The seminar gave a broad perspective of SSO. Early work to build up knowledge and to develop analysis methods for SSR in Sweden was shown. Methods of analysis and calculations for SSR and SSTI were presented both by TSOs and by manufacturer of equipment and they revealed the complexity of the field and the insight needed to deal with the potential problems. Mitigation methods both for SSR and SSTI were shown by manufacturer of controlled series compensation and by manufacturer of HVDC. Protections against SSR with respect to measurement challenges including new filtering techniques were demonstrated from the manufacturer side. Good operational experience was reported by the Swedish TSO when using the new protection on the series compensated lines.

The introduced filtering technique and the associated protection can be seen as new features which enhance the protection against SSR by making protection actions more secure.

Despite established methods to calculate and analyse SSR and SSTI there are still challenges due to the numerous of cases to be analysed for many complex network configurations. Setting calculations of the SSR protections may also be a challenging task. With the increasing number of HVDC links introduced into the grid SSTI may be as important as SSR to consider with respect to mitigation. Possibly it will also have some impact on the protection for synchronous generators.

4 Appendix A: Seminar program

PROGRAM:

09.00 **Coffee and registration**

09.30 Welcome, *Monika Adsten, Energiforsk, Sweden*

09.40 Introduction, *Per Lamell, Forsmarks Kraftgrupp, Moderator*

10.00 Subsynchronous resonance and Torsional interaction - Background and Physical understanding, *Kenneth Walve*

10.30 SSR analysis and design of SSR protection in Sweden, *Per-Olof Lindström, Svenska Kraftnät*

11.15 Experiences from SSTI-studies in HVDC projects, *Adil Abdalrahman, ABB Power Grids, HVDC*

12.00 **Lunch**

13.00 TCSC Introduction and its capability on SSR Mitigation, *Hector Latorre, ABB*

13.45 SSR Introduction and theoretical SSR amplitudes, *Stefan Roxenborg, ABB*

14.00 SSR field observations, *Tord Bengtsson, ABB*

14.30 Design of numerical SSR protections using ABB 670 Series IEDs *Zoran Gajic, ABB*

14.55 **Coffee**

15.10 Experience from the Swedish TSO in running the new protection, *Håkan Eriksson*[1]*, Svenska Kraftnät*

15.30 Experience from the Finnish TSO, *Tuomas Rauhala, Fingrid Oyj*

16.00 Discussion

16.30 End of seminar

[1] Presentation held by Per-Olof Lindström, Svenska Kraftnät

SUB SYNCHRONOUS OSCILLATIONS

This is a report from a seminar arranged to spread knowledge and to discuss experiences of subsynchronous oscillation that can affect nuclear power plants as consequence of grid interaction. Several aspects as methods of analysis and calculation, mitigation methods and protections issues were included in the seminar program.

The purpose of the seminar was to gather people from the nuclear industry, nuclear authorities, transmission network operators, researchers from universities, equipment manufacturers and consultants to discuss and to spread knowledge and experience about different kinds of resonance phenomena. Such phenomena could affect large steam driven turbine-generators sets as those utilized by the nuclear power plants in Finland and Sweden.

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