FREQUENCY SCANNING PROGRAM FOR SSR STUDIES IMPLEMENTED TO FUNCTION IN CONNECTION OF PSS/E POWER FLOW ANALYSIS PROGRAM

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Abstract – As risk of growing or sustained subsynchronous oscillations due to subsynchronous resonance (SSR) in transmission system is studied, tool used for preliminary analysis is commonly based on frequency scanning method. This paper presents implementation and verification of a frequency scanning program, which is designed to function in connection of PSS/E power flow program in order to be used as a part of normal network planning process. Thus exact and up-to-date network models used in power flow studies can also be used in frequency scanning studies. The frequency scanning program also applies some of the power system analysis methods provided by PSS/E environment. The developed program is capable to study the damping of subsynchronous oscillations using two well-established frequency scanning techniques. Their implementation is verified using the IEEE 2nd benchmark model for SSR studies. The results of verification using both of the methods are presented and compared in this paper.

Keywords: Subsynchronous resonance, SSR, torsional interaction, frequency scanning, damping analysis, synchronous machine, computational methods

1 INTRODUCTION

Interaction phenomena between power system series capacitors and turbine-generator units on a frequency range below nominal system frequency f_o is called subsynchronous resonance (SSR). Subsynchronous resonance is divided in three different categories based on interaction principles. Induction generator effect (IGE) is purely electrical system based phenomenon leading to self-excitation of subsynchronous oscillations when the negative subsynchronous resistance of generator rotor circuit exceeds the sum of the generator armature and the network resistances. Amplification of subsynchronous oscillations is also possible if the electrical resonance frequency f_{en} caused by series compensated transmission lines is close to the natural torsional resonance frequency f_n of the mechanical system consisting of turbine-generator unit. This SSR related electromechanical interaction phenomenon is known as torsional interaction (TI). Disturbances in power systems may cause severe stresses on turbine-generator shaft. In series compensated networks these disturbance related oscillations may be amplified if the resonance frequency of electrical system is close to the torsional resonance frequency of the mechanical system. This interaction phenomenon is called torsional amplification (TA). [9]

As growing subsynchronous oscillations may in extreme cases even cause a shaft failure, risk of subsynchronous resonance must be carefully analysed when series capacitors are installed in power system or when remarkable structural changes take place in series compensated transmission network. [1]

There are three main methods used in subsynchronous resonance studies; frequency scanning method, eigenvalue analysis and time-domain analysis. Contrary to the two other methods frequency scanning has traditionally been used in preliminary studies of subsynchronous resonance in order to gain insight of the most critical power system switching conditions considering the damping of subsynchronous oscillations. After frequency scanning studies the two more complex and more time-consuming methods can be applied to analyse the risk of growing oscillations more carefully. [2]

As the processing capacity of personal computers has drastically increased during last decade, risk of SSR in large power systems can be evaluated effectively using both time-domain analysis and eigenvalue analysis. However, most complete and regularly updated power system models are still commonly those used for power flow and fault current studies. Thus benefits of any SSR analysis program using those same power flow models are evident. In addition to the fact that there is no need neither to reduce the existing model nor to create a completely new power system model for the SSR studies, the functions provided by the power flow program itself can be used for example to compare different switching or loading conditions of the studied system. Additionally the usage of complete power system model allows the verification of validity of the reduced models used for example in time-domain analysis of subsynchronous resonance.

Describing all the equations related to the implementation of frequency scanning program is not in the scope of this paper as they all have been presented in various papers and books published during last decades. This paper targets especially to describe the various aspects to be considered in implementation of frequency scanning program. Instead of presenting equations used during implementation, publications where they can be found are referred.

2 THEORY OF FREQUENCY SCANNING ANALYSIS

Frequency scanning technique is based on analysis of electrical system impedance on sub- and corresponding supersynchronous frequency range. For analysis of torsional interaction due to SSR there are two basic approaches how the electric system damping can be determined based on the impedance values. These two approaches will be referred in this paper as damping coefficient analysis and damping torque analysis. In literature they are also referred frequency scanning technique and synchronizing and damping torque analysis [2], respectively. Also two other SSR phenomena can be evaluated based on the behaviour of the power system impedance on subsynchronous frequencies. Analysis of the sustained or growing subsynchronous oscillations due to induction generator effect and torsional amplification is referred in section 3.5.

2.1 Damping coefficient analysis

Damping coefficient analysis of torsional interaction caused by subsynchronous resonance is based on the analysis of sub- and supersynchronous torques caused by subsynchronous rotor oscillations [3]. As a result of the analysis the electrical damping on subsynchronous frequencies can be estimated using approximate relation,

$$D_{en} = \frac{1}{2 \cdot f_n} \cdot \left[\left(f_o - f_n \right) \cdot \frac{R_{sub,n}}{R_{sub,n}^2 + X_{sub,n}^2} - \left(f_o + f_n \right) \cdot \frac{R_{super,n}}{R_{super,n}^2 + X_{super,n}^2} \right] \quad , \quad (1)$$

where $R_{sub}+j \cdot X_{sub}$ = impedance seen from behind the study generator at frequency $f_n=f_o-f_{en}$
$R_{super}+j \cdot X_{super}$ = impedance seen from behind the study generator at frequency $f_{n,super}=f_o+f_{en}$

This approach was successfully applied in the frequency scanning program, which was used in connection IEEE 2nd benchmark model [4] in order to compare the frequency scanning method with the main two other SSR analysis methods.

2.2 Damping torque analysis

Concept of synchronizing and damping torque were known well before torsional interaction phenomena caused by subsynchronous resonance was recognized [5]. Definition of damping and synchronizing torque is based on the study of the synchronous machine response to small amplitude rotor oscillations. As the same principle was originally used to derive equation for damping coefficient analysis [3], later also damping torque analysis were proved to be suitable for SSR analysis method [6]. Damping and synchronizing torque k_e is given,

$$k_e(j \cdot \lambda) = K_e + j \cdot \lambda \cdot D_e \quad , \quad (2)$$

where K_e = synchronizing torque
$\lambda \cdot D_e$ = damping torque
$\lambda = f_n / f_o$.

Unlike damping coefficient described in section 2.1 damping and synchronizing torque can basically be defined both for mechanical and electrical system. It is well known that for the mechanical system especially the damping torque is small and extremely difficult to determine reliably [7]. Thus only the electrical damping torque is given by the frequency scanning program. From equation (2) the value of electrical damping corresponding the electrical damping coefficient given in equation (1) can be easily derived,

$$D_e = \frac{\mathrm{Im}\{k_e(j \cdot \lambda)\}}{\lambda} \quad . \quad (3)$$

2.3 Modal damping

Electrical damping alone doesn't give any exact information considering the possibility of growing or sustained subsynchronous oscillations due to torsional interaction caused by SSR. To determine parameter, which is comparable with the mechanical damping of the studied turbine-generator, also the behaviour of the mechanical system on the studied torsional frequency must be considered. The parameter in question is called modal electrical damping. It is defined using the electrical damping D_{en} and the modal inertia H_n of the mechanical system corresponding the natural torsional frequency f_n under study,

$$\sigma_{en} = \frac{D_{en}}{4 \cdot H_n} \quad . \quad (4)$$

Now the total modal damping $\sigma_{n,tot}$ of the electromechanical system can be defined using the modal electrical damping σ_{en} and the modal mechanical damping σ_{mn},

$$\sigma_{n,tot} = \sigma_{en} + \sigma_{mn} \quad . \quad (5)$$

The value of mechanical damping is typically very small on subsynchronous frequencies and it is practically impossible to determine it without field tests [7]. Because of the nature of the field tests values of the mechanical damping are not always available. Therefore in SSR analysis the mechanical damping can be either assumed to be zero or an approximate value like,

$$\sigma_{mn} = 0{,}002 \cdot f_n \quad , \quad (6)$$

can be used [7].

If the value of total modal damping $\sigma_{n,tot}$ remains negative, there is a risk of growing subsynchronous oscillations due to the torsional interaction caused by SSR. In such case more detailed studies using eigenvalue or time-domain analysis are strongly recommended.

3 IMPLEMENTATION OF FREQUENCY SCANNING PROGRAM ´´FSCAN´´

3.1 Determination of sub- and supersynchronous network impedance

As the frequency scanning technique is based on the analysis of the sub- and supersynchronous impedances seen from behind of the generator under study, successful implementation of the method used to determine the impedance is naturally crucial. The main alternatives for network subsynchronous impedance determination are:

- impedance calculation based on voltage response of the subsynchronous current injection
- reduction of the network on the circuit theory basis
- solving the Thévenin impedance using the system impedance matrix.

Using subsynchronous current injection for impedance determination was not a real alternative in this case as the program was designed to function as a part of power flow program. Hence its nature as passive component analysis tool does not allow use of dynamic excitation signals. As the power system models used in power flow analysis usually consists of several thousands nodes implementation of a function capable to perform reduction on circuit theory basis was not very well adapted to the purpose. Also usage of the system impedance matrix in order to define the Thévenin impedance seen from the generator terminals proved to be complicated because the elements of the matrix cannot be adapted in straightforward way using the functions provided by the power flow software.

However, Thévenin impedance can be obtained using fault current calculation functions provided by the software. Now by disconnecting the studied generator from the network, using passive network preconditions i.e. all node voltages equal $1\angle 0°$ p.u. and performing three phase fault with zero fault impedance at the generator terminal, the network impedance seen from the generator terminals can be easily solved.

After all, there was no need to use the calculated fault current to solve Thévenin impedance as the impedance itself was given in the fault current results provided by the program. For some reason there were minor differences between the Thévenin impedance given by the program and the impedance solved using the relation of pre-fault voltage and fault current. The reason for this remained unclear as the exact methods used in PSS/E to solve these values are not known.

In order to gain the Thévenin impedance related to sub- or supersynchronous frequency of interest all the inductive and capacitive elements of the network are scaled to correspond the studied frequency before the short circuit calculation is performed. A special function to scale all the power system components was implemented for this purpose. By using personal computer with 700 MHz processor and 128 Mt of RAM memory performance of the function takes approximately 20 seconds to scale the network components of 2000 node network to correspond certain sub- or supersynchronous frequency. This processing speed can be considered reasonable for SSR studies due to their infrequent nature.

3.2 Load modeling

Power system loads tend to improve the electrical damping and therefore they can be neglected in order to gain conservative study results. Nevertheless, power system loads may have significant effect on the damping of torsional interaction, if large amount of load is located close to the studied generator unit. As in power flow simulations loads are usually modeled as constant power loads they must be converted to impedances before performing the frequency scanning.

Straight conversion of real power load to resistances and reactive power loads to inductances is naturally unrealistic. Therefore the load connected to the studied node is divided in two parts: the other part is converted to passive inductive element describing characteristics of motor load and the other is similarly converted to resistive element corresponding the approximate amount of resistive loads like heating elements. The following equations used for load conversion are based on principle, which is proved experimentally [8] to be adequate for frequency scanning studies:

$$G_{load,\,p.u.} = \frac{S_{load}\cdot(1-k_{motor})}{S_{base}} \quad , \quad B_{load,\,p.u.} = \frac{S_{load}\cdot k_{motor}}{x''_{d,motor}}\cdot\frac{1}{S_{base}} \quad , \quad (7)$$

where S_{load} = total load connected to node
k_{motor} = proportion of motor load, e.g. 60 %
$x''_{d,motor}$ = typical subtransient reactance of motor, for example 0.135 p.u.

3.3 Generator modelling

The generator model used typically in frequency scanning studies is second order two-axis model from which sub- and supersynchronous impedances can be derived either based on equivalent circuit (figure 1) based impedances [4] or operational parameters [6],

$$\begin{cases} L_d(j\cdot\lambda) = L_d\cdot\dfrac{(1+j\cdot\lambda\cdot T'_d)(1+j\cdot\lambda\cdot T''_d)}{(1+j\cdot\lambda\cdot T'_{d0})(1+j\cdot\lambda\cdot T''_{d0})} \\ L_q(j\cdot\lambda) = L_q\cdot\dfrac{(1+j\cdot\lambda\cdot T'_q)(1+j\cdot\lambda\cdot T''_q)}{(1+j\cdot\lambda\cdot T'_{q0})(1+j\cdot\lambda\cdot T''_{q0})} \end{cases} . \quad (8)$$

The parameters given to the program are common stability parameters (see appendix A) from which the time constants or winding impedances shown in equation (8) and figure (1), respectively, can be determined using well-known relations.

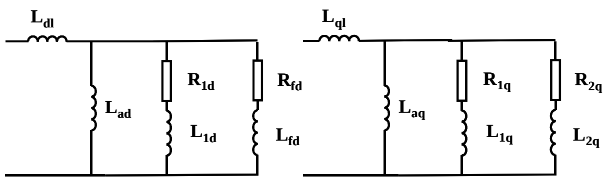

Figure 1: 2nd order model of rotor circuit for d- and q-axis

3.3.1 Effect of rotor model on electrical damping

Studies regarding the effect of rotor models on the analysis of torsional dynamics have proved that the electric machine rotor model used in the studies affects the level of conservativeness in analysis results [9]. The classic rotor model is the 2nd order two-axis model (shown in figure 1), which is commonly used in power system analysis programs. This model is typically derived using common stability parameters, which are also used as input data (see Appendix A) for the frequency scanning program. However, according to study results traditional 2nd order model provides somewhat pessimistic study results as the torsional dynamics are studied. In order to gain more conservative results either 2nd order model including the mutual inductance L_{f1d} proportional to fluxes linking the field and rotor body circuit (shown in figure 2) or 3rd order model with or without the inductance L_{f1d} should be used [9].

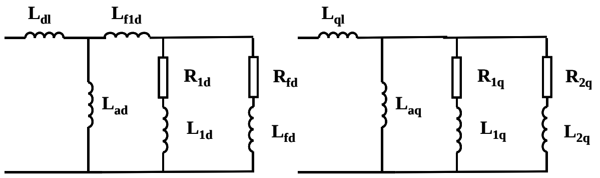

Figure 2: 2nd order model of rotor circuit for d- and q-axis including the mutual inductance L_{f1d}

Unfortunately the more detailed rotor models are in practice derived using the results of the standstill frequency response (SSFR) test, which are not commonly available and inconvenient to use in power system analysis programs. Therefore conventional 2nd order two-axis model was chosen for generator modeling in order to maintain both the generality of the models used and the usability of the program. Still, an implementation of either more detailed rotor models or even usage of SSFR data itself in the frequency scanning program is rather simple. In order to improve the conservativeness of the results given by the program their effect will be analysed in further studies.

3.4 Modeling of the mechanical system

The nature of frequency scanning studies does not practically allow analysis of complex non-linear systems such as mechanical system consisting of the rotating masses of turbine-generator. However, using mode transformation the complex mechanical system can be reduced to several simple mechanical systems, each of which describe the behaviour of the total system on certain natural torsional frequency [10]. The natural torsional frequencies and corresponding modal inertias can easily be calculated from the lumped parameter model of turbine-generator using mathematical analysis software. Therefore no real need for implementation of modal parameter solving functions in frequency scanning program exists. Thus modal parameters can be used as input parameters for the program in case the total subsynchronous modal damping of certain torsional frequency is of interest.

3.5 Results given by the program

Depending on the input data given by the user the program solves different values regarding the behaviour of the network on sub- and supersynchronous frequency range. If user defines only the subsynchronous frequency range to be studied and power system node from which the scanning is performed, program solves the behaviour of network impedance from the given node on sub- and corresponding supersynchronous range.

If the generator file given to the program does not include information related to generator loading conditions, program solves automatically the electrical damping on given frequency range using damping coefficient method. In addition program solves the total impedance over the same frequency range seen from behind the generator under study. This impedance can be used to analyze the possibility of growing subsynchronous oscillations due to induction generator effect and torsional amplification [11]. When also the generator loading is included in the input file, the program solves the electrical damping based on damping torque analysis. The structure of generator input file is shown in appendix A.

Finally, if also mechanical data of the study generator is given to the program using input form shown in appendix A, the program solves the modal electrical damping for all the modes given in input file. Modal electrical damping is calculated using the electrical damping values calculated using both the damping coefficient and the damping torque method.

4 VERIFICATION OF THE FREQUENCY SCANNING PROGRAM

Verification of the frequency scanning program was performed using System-1 presented in IEEE 2nd benchmark for SSR studies shown in figure 3. [4]

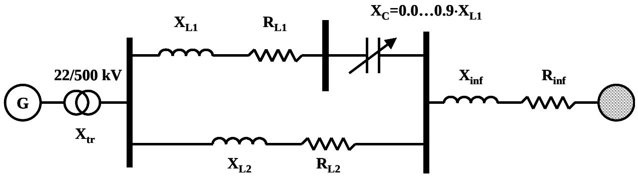

Figure 3: System-1 of the IEEE 2nd SSR Benchmark model

The results given by the program are compared to the results presented in connection of the benchmark model and to the results of PSCAD simulations. Also the results given by the different methods and generator models implemented to the frequency scanning program are compared in different loading conditions.

4.1 Comparison with results given in IEEE 2nd Benchmark for SSR studies

Comparison of the study results calculated using the frequency scanning program and the results given in connection of the 2nd benchmark model are shown in figure 4. The undamping is shown for the torsional vibration mode 1 for which f_n = 24.45 Hz. [4]

Both the results calculated using damping coefficient method and damping torque analysis are shown. Figure 4 shows that all the results are essentially very similar although the behaviour of the undamping given by the program doesn't match perfectly with any of the three different undamping graphs given in the benchmark. However, the compensation degree on which the maximum undamping is reached matches very well with the benchmark results as does also the shapes of the undamping graphs. Considering the maximum undamping the results given by the damping coefficient analysis are somewhat conservative, which can be considered as desirable characteristic of a tool used for preliminary analysis of SSR level.

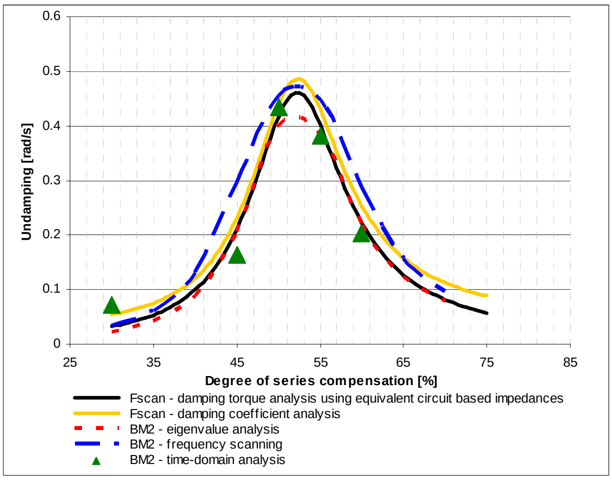

Figure 4: Undamping of mode 1 (f_n = 24.65 Hz) as a function of degree of series compensation

4.2 Comparison with results simulated using PSCAD under different loading conditions

Especially for the torsional oscillation modes whose mechanical damping increases only slightly as the generator loading increases from zero to nominal, the effect of generator loading on subsynchronous damping should be also studied. Since the reference results given in IEEE 2nd SSR benchmark model didn't consider the loading of the generator, System-1 was modeled using PSCAD/EMTDC transients simulation software in order to validate the implementation of damping torque analysis.

In figure 5 the results obtained from PSCAD simulations and the results of the frequency scanning program using the damping coefficient calculation as well as damping torque calculation are shown. In addition, for damping torque analysis results using both generator impedance determination methods presented in section 3.3 are shown.

Figure 5 shows clearly that when unloaded system is studied, all the results calculated using the frequency scanning program match very well with the results obtained using PSCAD. Nevertheless, the maximum undamping given by the damping torque analysis based calculation is somewhat lower than compared to the value given by the PSCAD simulation. Since frequency scanning is commonly used as a tool for preliminary SSR studies, it is important that certain level of conservativeness is gained in the frequency scanning compared to the more exact analysis methods. In this case undamping given by the damping coefficient method gives conservative results over the whole study range and thus the requirement of conservativeness is fulfilled for unloaded generator.

The largest differences between the methods used in implementation of the frequency scanning program were reached when the generator was loaded close to its maximum (figure 6). When figures 5 and 6 are compared it can be clearly seen how the maximum undamping increases as the generator loading increases. The undamping calculated using the damping coefficient method is not affected by the change in loading conditions. Thus maximum undamping calculated is now about 15 % lower than the maximum value determined using PSCAD.

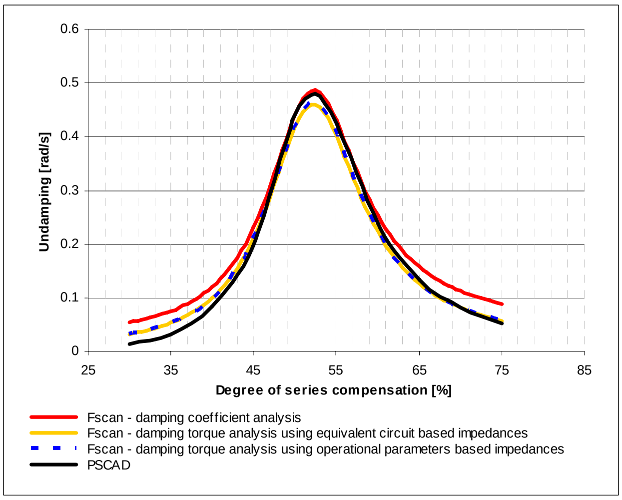

Figure 5: Undamping of mode 1 (f_n = 24.65 Hz) as a function of degree of series compensation as generator is unloaded

Undamping calculated using damping torque analysis matches well with values based on PSCAD simulations. As the undamping given by the frequency scanning program is slightly lower than the one given by PSCAD, it seems that small modifications should be made in the frequency scanning program in order to fulfill the requirement of conservativeness.

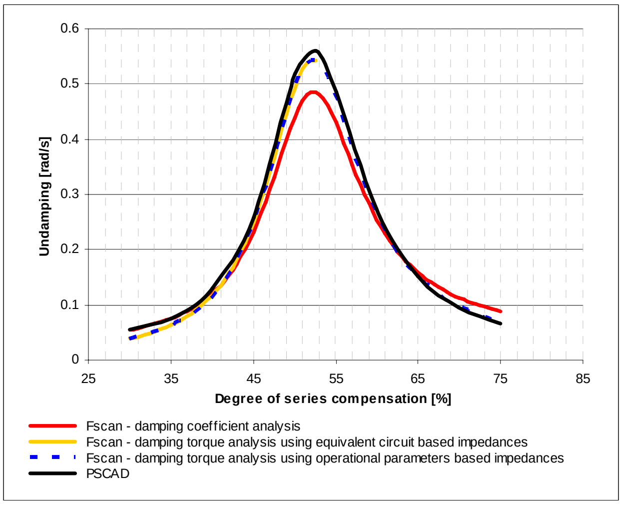

Figure 6: Undamping of mode 1 (f_n = 24.65 Hz) as a function of degree of series compensation as generator is working at close to its maximum load

The effect of generator impedance calculation method used can be noticed from figures 5 and 6 to be regardless as there is only minor difference between the results given by the methods.

4.3 *Study of different turbine-generator structures*

In order to gain more information considering the correspondence between results given by the frequency scanning program and PSCAD, the structure of turbine-generator of the benchmark model was varied using several generators presented in different publications. In figure 7 the results of the frequency scanning are compared with results given by PSCAD in situation, where Navajo 892 MVA turbine-generator presented in the 1st IEEE SSR benchmark [12] is used as a study generator. In the figure undamping is shown for the first torsional mode, f_n = 15.71 Hz, of the turbine-generator.

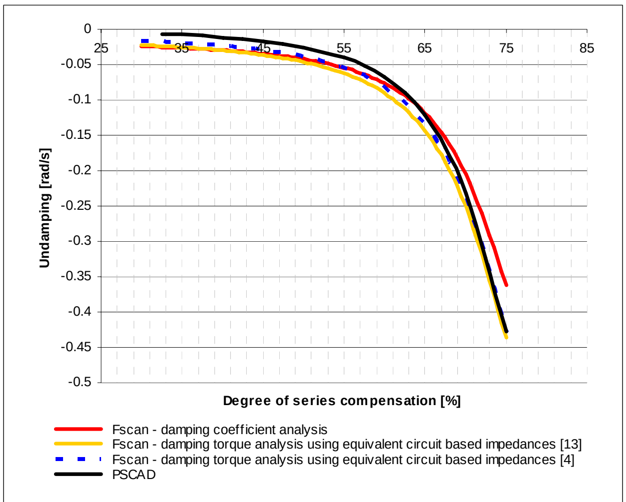

Figure 7: Undamping of mode 1 (f_n = 15.71 Hz) as a function of degree of series compensation as the Navajo generator is working at close to its maximum load

Results shown in figure 7 are basically very similar to the results shown earlier. For loaded generator the damping coefficient calculation seems to provide pessimistic results considering the maximum value of the undamping. However, opposite to the study presented earlier in this paper, the damping torque calculations provide now slightly conservative results compared to the results obtained using PSCAD simulations. As shown in figure 7, also the method used to calculate the rotor body resistance from the stability parameters [4,13] can also be used to slightly increase the level of conservativeness.

During these studies using different turbine-generator structures the level of conservativeness in results varied between generators as shown in figures 6 and 7. Overall, the correspondence between the results given by the frequency scanning and PSCAD was very good. A method to increase the level of conservativeness would be still of importance in order to guarantee the conservativeness for all generator structures. However, for large network studies the conservativeness can also be obtained for example by disregarding the effect of the power system loads on the subsynchronous damping.

5 CONCLUSIONS

It is evident that SSR study tool designed to function in connection of an on-daily-basis used power system analysis environment will make it easier for power system operators to approach the SSR phenomenon and to gain more exact information regarding the SSR risk level in their system.

This paper presents a frequency scanning program, which is rather simple to implement to function in connection of PSS/E power flow analysis tool. The correct implementation of two well-established frequency scanning methods is successfully verified using IEEE 2nd benchmark model.

The results given by the program were compared with the results presented in IEEE 2nd benchmark model and the results obtained using PSCAD transients simulation program. Overall, the correspondence between the results was very good. However, conservative study results were obtained only for unloaded units as the study results of loaded units were in some cases slightly pessimistic. The possibilities to increase the conservativeness of the results using for example more detailed generator models or SSFR data will be analysed in further studies.

The implementation of the program must still be verified using larger power system models to ensure, that the chosen impedance determination method is proved to be valid also for more complex systems. Before this verification is successfully finished, the program shall not be used to study real SSR cases. However, the preliminary results obtained from large-scale system studies are promising.

Since the program is completely custom-made, adding options like the calculation of UIF to estimate the SSTI risk caused by HVDC links in the power system is easy especially as all the function of power flow software are easily adaptable. Also the use of higher order generator models or direct application of SSFR test results are possible to be implemented to the program afterwards, if their use is considered advantageous during further studies.

After the verification process using large-scale power system models is successfully finished, Finnish transmission system operator will apply the program as one of transmission system-planning tools.

6 REFERENCES

[1] IEEE SSR Working Group. "Reader's Guide to Subsynchronous Resonance". IEEE Transactions. Vol PWRS-7. No 1. February 1992. p. 150-157

[2] Padiyar K.R.. "Analysis of Subsynchronous Resonance in Power Systems". Kluwer Academic Publishers. MA, USA. 1999.

[3] Kilgore L.A, Ramey D.G., Hall M.C.. "Simplified Transmission and Generations System Analysis Procedures for Subsynchronous Resonance Problems". IEEE Transactions. Vol PAS-96. No 6. Nov/Dec 1997. p. 1840-1845.

[4] IEEE SSR Working Group. “Second Benchmark Model for Computer Simulation of Subsynchronous Resonance”. IEEE Transactions. Vol PAS-104, No 5. May 1985. p.1057-1066.

[5] Laible T.. “Die Theorie der Synchronmaschine in nichtstationären Betrieb“. Springer-Verlag. Berlin, Germany. 1952.

[6] Canay I.M.. “A Novel Approach to the Torsional Interaction and Electrical Damping of the Synchronous Machine, Part I: Theory and Part II: Application to an arbitrary network”. IEEE Transactions. Vol PAS-101. No 10. October 1982. p. 3630-3647.

[7] Walker D.N., Adams S.L., Placek R.J.. “Torsional Vibrations and Fatigue of Turbine-generator Shafts”. IEEE Transactions. Vol PAS-100. No 11. November 1981. p. 4373-4380.

[8] Agrawal B.L., Demcko J.A., Farmer R.G., Selin D.A.. “Apparent Impedance Measuring System (AIMS)”. IEEE Transactions. Vol PWRS-4. No 2. May 1989. p. 575-585.

[9] Atarod V., Dandeno P.L., Iravani M.R.. “Impact of Synchronous Machine Constants and Models on the Analysis of Torsional Dynamics”. IEEE Transactions. Vol PWRS-7. No 4. November 1992. p. 1456-1463.

[10] Jennings G.D., Harley R.G.. ”New Index Parameter for Rapid Evaluation of Turbo-Generator Subsynchronous Resonance Susceptibility”. Electrical Power System Research. Vol 37. Issue 3. June 1996. p. 173-179.

[11] Hall M.C., Daniels R.L., Ramey D.G.. “A New Technique for Subsynchronous Resonance Analysis and an Application to the Kaiparowits System”. IEEE Transactions. Vol PAS-96. No 4. July/Aug 1977. p. 1251-1255.

[12] IEEE SSR Working Group. “First Benchmark Model for Computer Simulation of Subsynchronous Resonance”. IEEE Transactions. Vol PAS-96. No 5. Sept/Oct 1977, p. 1565-1572.

[13] Kundur P.. ”Power System Stability and Control”. McGraw-Hill. NY, USA. 1994

7 APPENDIX

7.1 Appendix A

Format for generator input data:

```
X_l    R_a
X_d    X_d'    X_d''
X_q    X_q'    X_q''
T_do'  T_do''
T_qo'  T_qo''
MVA_base  kV_base
Vo     Po     Qo
```

Format for turbine-generator (mechanical) input data:

```
Total number of modes
fn of mode 1     Hn of mode 1
fn of mode 2     Hn of mode 2
fn of mode 3     Hn of mode 3
etc.
```