Damping Low Frequency Oscillations with Hydro Governors

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Abstract— **This paper presents a novel approach into damping inter area oscillations during poor grid conditions and low oscillation frequency ranges at the generator side. The method is based upon the application of a single input Power System Stabilizer to the actuators of hydro governor systems (PSS-G). One constraint thereby is the decoupling of the damping application from the standard operational functionalities such as primary control. The investigation is based upon a two-step approach: A principal feasibility investigation utilizing a Single Machine Infinite Bus-SMIB Model and a second step using a four generator two area model focusing on the interaction of the governor control path and the voltage control path. Local signals and signals derived from Wide-Area-Measurement System (WAMS) like speed deviation or accelerating power respectively voltage angle deviation have variously been used as input signals and compared by their impact on system damping.**
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***Index Terms*—Small Signal Stability, Hydro Governor, Inter Area Oscillations, Power System Stabilizer**

I. Introduction

Transmission grids in Europe are progressively facing critical operational situations characterized by high line loading, volatile and geographical centralized generation and security limit violations. The reasons are manifold, reaching from the increased number of actors in the liberalized electricity markets to massive integration of renewables and sagging realization of grid extension plans. Conventional generating units, mostly synchronous generators are partly substituted by must-run renewable units. These circumstances lead to a volatile oscillatory behavior of the power grid resulting from a permanently change in the constitution of the type of operating generation units and thus change in grid inertia.
The situation is in principle similar for most member countries of the ENTSO-E association with varying influences and consequences for system operation and stability depending on the local conditions.
As one of many consequences, such as higher frequency gradients or higher steady state frequency deviations, the small signal stability has become a demanding topic of increasing attention in the last decade. This is mainly resulting from highly stressed systems and the absence of adequate system damping resulting in poorly damped local oscillations or inter-area oscillations. Latter leads to the oscillation of groups of generators in different grid areas swinging with or against other groups, causing unwanted active power flows across wide grid areas. Under these conditions oscillatory stability is endangered preliminary due to two influencing factors [1]:

- The danger of generation losses as a consequence of loss of synchronism and
- The violation of transmission grid security limits and hence automatic power line disconnections depending on the actual system loading.

The worst case scenario in this manner is a cascade of line trips and furthermore major blackouts.

II. Situation in Scandinavia

Norway has had and still has a special power system characteristic compared to most European countries and also its Nordic neighbors. This is reflected in how the power grid is designed (grid topology and geographical distribution of generating units) and operated.
Furthermore the inter-area connections between several generating and consumer areas are often relatively weak. The reason is the large contribution of hydro power generation to the total energy consumption of almost 99 %, and the way these energy sources were developed and geographically distributed. The hydro resources were exploited individually

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in the past and very often industry consortiums or cities secured their own supply (an example is aluminum smelters) with the consumption either close to the source or supplied by their own power lines. The era of hydro power connected to the transmission grid (operated by Statnett) started in the early 20th century and especially in areas of higher mountains of the mid and western part of southern Norway or northern Norway (Norland), but geographically widely spread.

Also in Sweden (40 % -50% hydro power plants) large hydro units are located in the northern part of the country. The large distance from the hydro units to the main power consuming areas of the south forced a coordinated grid development to handle large power flows over great distances.

In Norway however, many areas of power surplus of the mid and western mountain areas were connected to the eastern power deficit area in various development stages. Also the connection to mid-Norway and further to northern Norway is quite weak.

Angle instability is seen typically at inter-area power transfer corridors, as between Norway and Sweden in the south - the Hasle corridor – or along 132/420 kV corridor in the North (the "Salten mode" - 0,6 Hz). The oscillations of Hasle are either towards Sweden (typically 0.50 Hz) or also towards Finland (0.35 Hz). The large power surplus of southern Norland towards mid Norway and also power interchange between areas of the western part makes angular stability often a problem. A lot of local oscillations have been seen especially on radial lines.

In Norway most generating units of sizes above 25 MVA are equipped with classical Power System Stabilizers. The nature of these stabilizers is mainly to damp the eigenmodes of the unit. This will always contribute to damping, but may not be optimal for all modes especially not for inter-area modes.

III. Objective and Simulation Models

The main objective of this work is to investigate potential of the hydro governor to act as a damping device. The classical generator side damping via the excitation control path shall thereby be extended by the utilization of the active power control path respectively the hydro governor. The aim of this novel approach is to improve the damping behavior of low frequency oscillations under weak grid conditions from the generator's perspective.

Utilizing a **Single Machine Infinite Bus**- SMIB system principle characteristics of the governor system equipped with a **P**ower **S**ystem **S**tabilizer-**G**overnor (PSS-G) are derived in a first stage. The advantage of this model is the absence of mutual coupling among generators and other controllers or other damping devices and thus the isolation of the dynamic characteristics of the hydro governor as a damping device.

The investigated governor, used is many modern hydro power plants, is an electrohydraulic type shown in Figure 1.

Due to the extension of the generator and controllers of the Single Machine Model by three more generators and interconnection lines the second stage **Multimachine Model** is deployed. The topology is related to the well-known Kundur two-area system described in [1], which is used in many small signal studies.

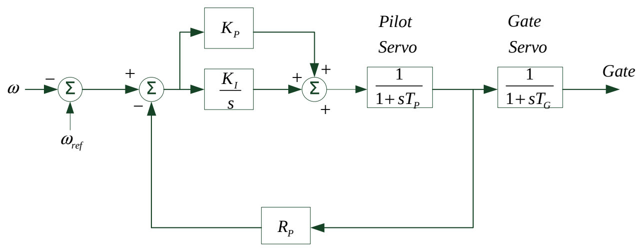

Figure 1 Block diagram of the electrohydraulic governor model, PI controller, pilot servo and gate servo

The controllers of the additional generators respectively the dynamic model structures and parameters basically rely on the recommendations in the respective IEEE documents in [2], [3] and [4]. On basis of this configuration the interaction of the controllers is of central concern. For each model the investigations are based upon linear theory as well as time domain simulations taking into account nonlinear behavior of the system.

IV. The Classical Power System Stabilizer PSS-E

A. General

The common used damping device Power System Stabilizer – PSS-E (**P**ower **S**ystem **S**tabilizer-**E**xcitation) is used to increase the damping of local or inter-area oscillations. The utilized control loop is the voltage control path with the advantage of a fast action devoid of additional mechanical actuator utilization. A widely used linear generator representation for the analysis of the PSS-E impact is the Heffron-Phillips or K-constant model shown in Figure 2. The structure and meaning of the constants is furthermore described in [5] in detail.

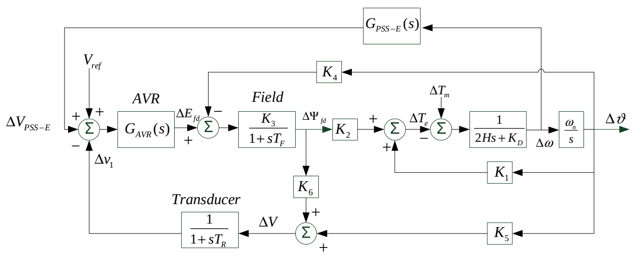

Figure 2 Block diagram of detailed system including changes in field flux linkage variation, Automatic Voltage Regulator-AVR realized as excitation system ST1A[2] and the effect of the PSS-E in K-constant representation [1]

From the basic idea the constants K1-K6 are derived by putting the system parameters in relation to the generator speed deviation and rotor angle deviation.

The resulting torque contributions from the excitation path ΔT_e in case of small deviations from the steady state can thus be separated into terms in phase with the speed deviation $\Delta\omega$ (damping torque component) and in phase with the rotor angle deviation $\Delta\vartheta$ (synchronizing torque component). In

2 Static excitation system, for further details see [2]

most small signal stability studies the contribution from the governor path ΔT_m is neglected. Typical settings for the PSS-E output limits are in the range of 3% up to 5% of the actual terminal voltage. This is due to the mutual influence among the PSS-E and the voltage control of the generator of concern respectively the voltage controls of neighboring generators.

B. Drawbacks

Even though the PSS-E is operating via the excitation system very fast and it can provide a positive impact on the damping the beneficial impact on damping during unfavorable grid conditions and high generator connection impedances is limited. The reason is the increased coupling among electrically neighboring generators (e.g. within a power plant with more than one generators, see [6]) resulting in increased influence on the voltage control. In this regard the limitations of the PSS-E output can significantly reduce the beneficial impact on the target oscillation. Furthermore in case of poorly damped inter-area oscillations the reduced efficiency in power oscillation damping can affect a wide range of the power system.

Additionally, the dependency of the damping behavior on the operating conditions of the generator also implies that the optimal settings for a PSS-E are varying depending on the prevailing grid conditions. This implies challenges for the parameterization of the PSS-E ([7], [8]). In order to solve these problems several robust parameterizations techniques have been developed, such as H_∞ methods, linear matrix inequalities or supervisory level power system stabilizers [9]. Optimization algorithms addressing the immanent change in operation conditions are presented in [10].

V. HYDRO TURBINE GOVERNOR AS DAMPING DEVICE PSS-G

A. General Issues

The focus in this work is on the behavior of hydro governors and their actuators in case of low frequency oscillations. For most of the small signal stability investigations the contribution of the hydro governor in terms of damping and synchronizing torque contributions has been neglected.

Here the contribution from the governor is analyzed with and without the effect of the PSS-G. Furthermore, the eigenvalue shifts for various PSS-G input signals are tracked using root locus plots. Special attention is thereby put on weak grid conditions with limited impact of the PSS-E as described in section IV.B.

The oscillation frequency range of interest where the investigation focuses on is defined in the region of oscillation frequencies below 0.5 Hz where the contribution of the governor is believed to be realistic regarding the actuator speed limits. This range is typically dedicated to inter-area oscillations.

B. Linear Approach – The Extended Heffron-Phillips Model

The general approach is structured stepwise, starting from a small, principle Single Machine Infinite Bus Model-SMIB to a more complex multimachine model. Principle relationships and feasibility considerations are based on a single synchronous generator connected to an infinite bus. In a four generator multimachine model interactions between two areas and the mutual interactions between control loops on inter area oscillations are illuminated.

The standard Heffron-Phillips model in Figure 2 is therefore extended by the governor control path including the PSS-G, both summarized in the complex transfer function $G_{Mechanical(s)}$. In Figure 3 the extended Heffron-Phillips representation of the synchronous generator with PSS-E including the governor system and the PSS-G for a single machine model is shown.

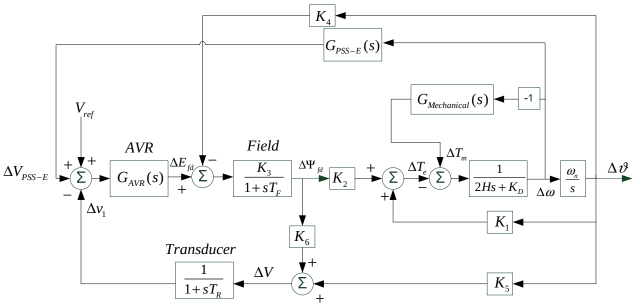

Figure 3 Block diagram of extended Heffron-Philipps model including changes in field flux linkage variation, AVR realized as excitation system ST1A[3], the effect of the PSS-E, governor and PSS-G

Additionally to the damping and synchronizing torques provided by the voltage control loop, represented by the constants K_1-K_6 and optionally the transfer function G_{PSS-E}, the contributions from the governor control path is represented by the transfer function $G_{Mechanical}(s)$ including the governor and PSS-G characteristics.

C. Derivation of Governor Impact

A simplified representation of the extended Heffron Phillips model is given in Figure 4. The voltage control loop (constants K_1-K_6) is thereby represented by the complex transfer function $G_{Electrical}(s)$ whereas the governor control path including the PSS-G is summarized in $G_{Mechanical}(s)$.

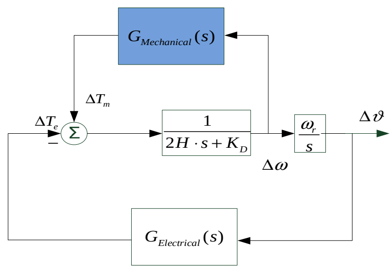

Figure 4 Summarized Heffron-Phillips model for the electrical control path $G_{Electrical}(s)$ and the mechanical control path $G_{Mechanical}(s)$ including PSS-G

The perturbation of the mechanical torque ΔT_m is at the complex frequency $s=j\omega$ is proportional to the speed deviation $\Delta\omega$. Splitting $G_{Mechanical}(s)$ in real and imaginary part the generalized transfer function for the mechanical system is given by

[3] Static excitation system, for further details see [2]

$$\Delta T_m = G_{Mechanical}(s) \cdot \Delta\omega = \\ = Real\{G_{Mechanical}(s)\} \cdot \Delta\omega + j \cdot \Delta\omega \cdot Imag\{G_{Mechanical}(s)\} \qquad (1)$$

where Real and Imag correspond to the real part respectively the imaginary part of ΔT_m.
The first term in phase with $\Delta\omega$ is dedicated to the damping term KD. The second term in phase with $(j \cdot \Delta\omega)$ needs to be rearranged and split up in terms in phase with $\Delta\omega$ (damping torque) and in phase with $\Delta\vartheta$ (synchronizing torque) using the relation taken from Figure 4

$$\Delta\vartheta = \frac{\omega_r}{s} \cdot \Delta\omega \qquad (2)$$

Hence, for a system eigenvalue λ representing an oscillation mode of interest and introducing ω_r as the rated angular velocity the contribution from the governor side can be determined with

$$KD_{\Delta Tm} = \left[Real\{G_{Mechanical}(s)\} + \frac{Imag\{G_{Mechanical}(s)\} \cdot Real\{\lambda\}}{Imag\{\lambda\}} \right]$$

$$KS_{\Delta Tm} = \left[\frac{Imag\{G_{Mechanical}(s)\} \cdot Imag\{\lambda\}}{\omega_r} + \frac{Imag\{G_{Mechanical}(s)\} \cdot Real\{\lambda\}^2}{\omega_r \cdot Imag\{\lambda\}} \right] \qquad (3)$$

Consequently, KD_{Tm} is the damping component and KS_{Tm} is the synchronizing component provided by $G_{Mechanical}$. In the following chapter the damping components are illuminated in more detail for varying grid conditions.

VI. Comparisson of the Linear Characteristics of the Governor and Voltage Control Path

The results derived in this chapter are based on the investigation of the SMIB model. As described in chapter IV.B. the impact of damping control action via the voltage control path leads to mutual coupling with other voltage control devices in electrical neighborhood and thus reveals a sensitivity to changes of the damping behavior in case of changes in grid conditions.
From further interest in this regard is the robustness of the governor control path (without PSS-G) to changes in grid impedance, infinite bus voltage and the frequency response of the transfer function $G_{Mechanical}$. Thus, equation (3) is applied to the governor control path ($G_{Mechanical}$) observing the contributions of the damping torque component KD_{Tm} for various grid conditions. Analogously, following the descriptions in [1] chapter 12, the same routine is done for the voltage control path ($G_{Electrical}$) resulting in the damping torque component KD_{Te}.
In Figure 5 the damping torque components KD_{Te} and KD_{Tm} as well their sum are shown for various grid impedances (grid impedance given in p.u. in terms of generator base impedance). The damping torque component KD_{Te} is decreasing with increasing grid impedance. The contribution from the mechanical transfer function $G_{Mechanical}$ is negative but almost constant for the various grid impedances. Thus, the decay in the damping torque from the electrical side is superposed by a constant decrease from the mechanical side leading to the resulting damping torque KD_{sum}.

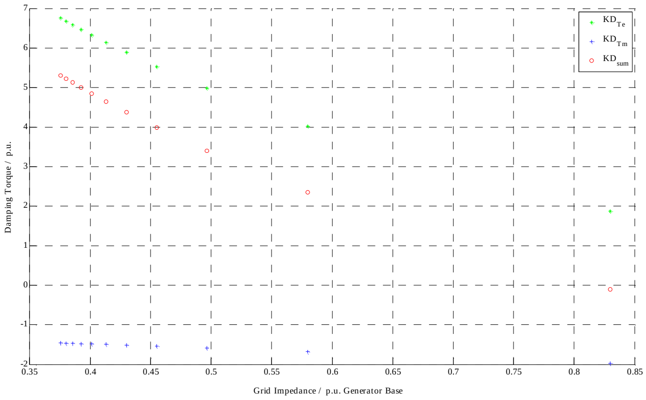

Figure 5 Damping torque components of $G_{Electrical}$ (KD_{Te}) and $G_{Mechanical}$ (KD_{Tm}), variation of grid impedance in terms of generator base impedance

For the variation of the infinite bus voltage from 0.9.p.u. to 1.1 p.u. the damping torque provided by the excitation system increases whereas the contributions from the governor control path damping remain almost constant but negative. The associated scatterplot is displayed in Figure 6.

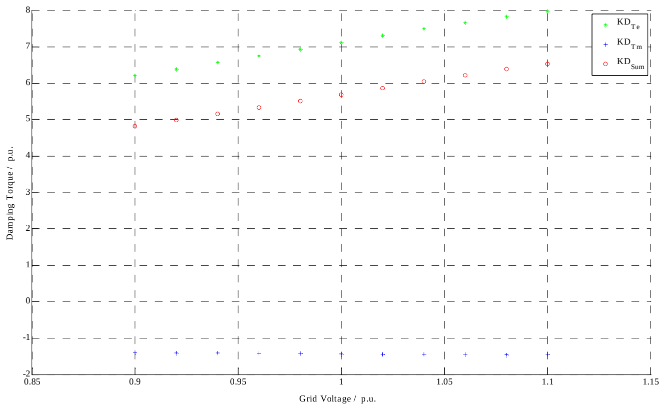

Figure 6 Damping torque components of $G_{Electrical}$ and $G_{Mechanical}$, variation of infinite bus voltage

Concluding Figure 5 and Figure 6 the governor control path provides negative damping for the investigated scenario. Furthermore a robust damping behavior regarding changes in grid impedance and bus voltage is observed whereas the voltage control path shows high sensitivity.
In Figure 7 the frequency response of $G_{Mechanical}(s)$ is derived in the oscillation frequency of interest from 0.01 Hz up to 2 Hz. It can be observed that the governor system provides negative damping to the system in the frequency range from 0.05 Hz to 0.7 Hz. Similar behavior for governors of steam turbine systems has been observed in [7], [8] and [11]. The synchronizing component is very close to zero throughout the changes in frequency.

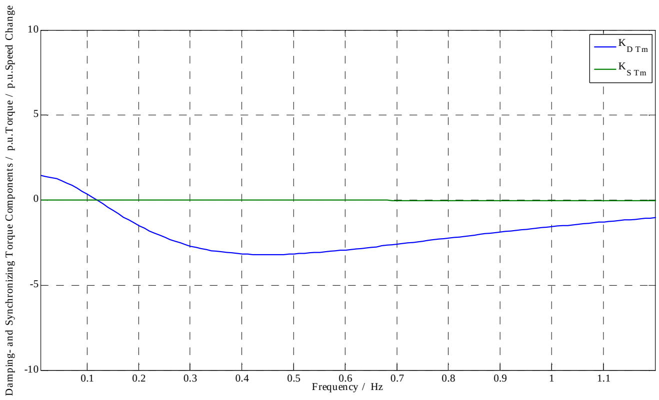

Figure 7 Damping and synchronizing torque derived from the frequency response of $G_{Mechanical}$

VII. Simulation Results

The results shown in this chapter are derived from simulations utilizing the two-area multimachine model. The occurring inter area mode between area 1 and area 2 is thus the target mode for the parameterization of the PSS-G. The input signal for the PSS-G is chosen to be the local signal P_d (accelerating power, difference between mechanical active power and electrical active power of the generator) and the Wide Area Measurement System- WAMS signal of the inter area tie line voltage difference $d_{theta\ line}$.

The optimized PSS-G parameters for the target mode are derived by the application of the residue method [12] to the mechanical inter-area oscillation.

A. Modal Analysis

The modal analysis gives insight to the linear potential of the governor influence on damping the target mode. Thus, the PSS-G variously connected with P_d and $d_{theta\ line}$ is compared to the base case scenario. The root shifts are drawn in Figure 8 and illustrate the vertical shift of the root corresponding to the inter area mode (marked with the blue frame).

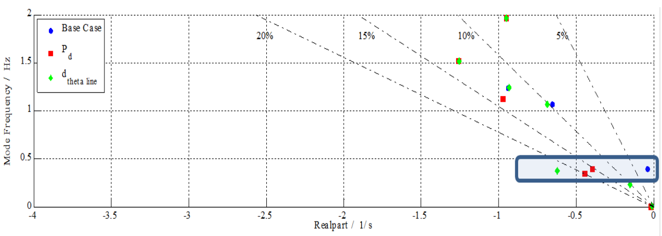

Figure 8 Scatter plot of the poles for the base case and PSS-G using input signals accelerating power P_d and inter-area tie line voltage angel difference $d_{theta\ line}$; root shift of inter area mode marked in blue frame

From Figure 8 one can observe that the base case inter-area mode provides a poor damping of 2 % at an oscillation frequency of 0.4 Hz. Furthermore, the tie line voltage angle difference is resulting in a mode damping of more than 20 %. The PSS-G supplied with P_d leads to a damping of the mechanical oscillation of 15 % whereas the controller mode is very close with a damping of 20 %.

In Figure 9 the corresponding mode shape is shown.

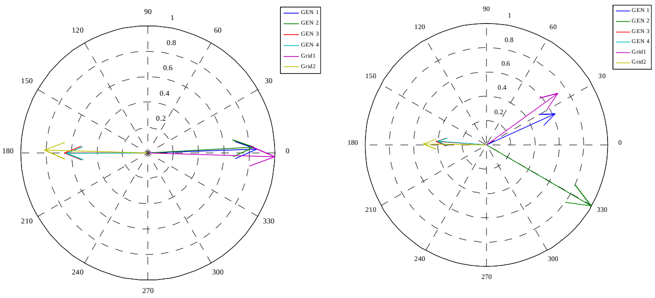

Figure 9 Mode shape of the inter area mode, base case (left), PSS-G active(right); exemplary using P_d as input signal

The PSS-G is applied at generator 2 resulting in the dominating speed deviation.

B. Time Domain Simulations

In the time domain simulation the PSS-G using the local signal P_d as input signal is investigated more closely. The principle conclusion is similar using other input signals such as $d_{theta\ line}$ or tie line active power. The excitation of the generator oscillations results from a three phase short circuit in the middle of the inter-area tie line. The fault is cleared after 150 ms.

The upper picture in Figure 10 shows the time courses of the base case. After the decay of the well damped local oscillations at around t=10s the inter area mode can be observed. Generator 1 and 2 in area 1 are swinging against generator 2 and 4 in area 2. The inter-are oscillation frequency is estimated with 0.4 Hz.

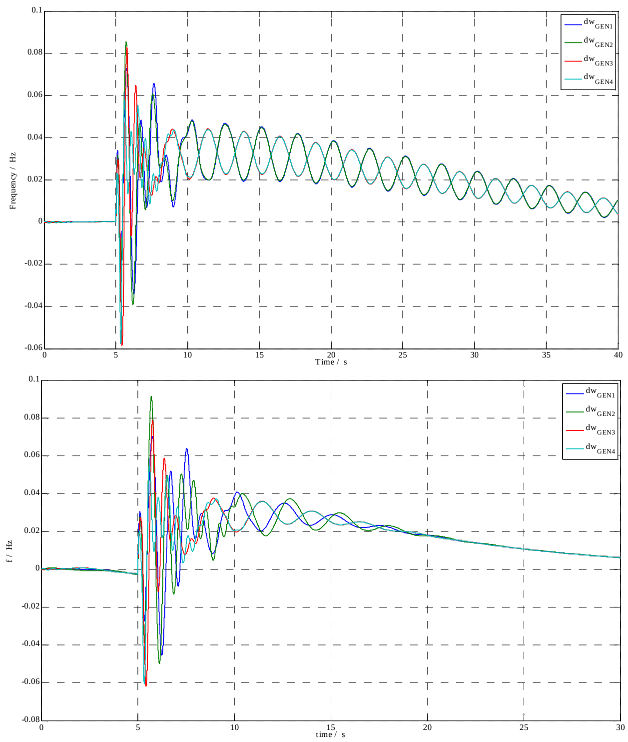

Figure 10 Speed deviations of the generators; Base case in upper picture, PSS-G using P_d as input signal in lower picture

In the lower picture one can see the time course with the PSS-G active at generator 2. The inter area oscillation respectively the target mode is decayed after 20 s.

VIII. Major Results

As a major result the capability of digital hydro governor systems to act as a damping device was derived, demonstrated for an inter-are oscillation with a frequency of 0.4 Hz.

The governor path has shown negative damping contributions over a wide range of oscillation frequencies. In most stability studies this amount is rightly neglected. However, for very poor damped low frequency modes the amount of positive damping provided by the excitation path has been shown to be in the range of the negative contribution provided by the governor. In such cases the inclusion of the governor system damping is recommended.

From the analysis of the voltage and governor control path it is concluded that the governor control path is robust against changes in grid impedance and bus voltage and thus against changes in grid conditions. In contrast the contribution of the voltage control path to system damping is sensitive to both, grid impedances and terminal voltage. This implies also that the impact of the voltage control path respectively the PSS-E is saturated as the grid conditions are poor.

In the time domain simulations the potential determined from the linear analysis is tested under the restrictions of the actuator speed limits. The limitation in the impact on system damping of the governor is predominantly given by the respective speed limits of the actuators of the hydro governor. Depending on the applied turbine type these limitations can vary strongly weather the limiting element is the vane system of a Francis type or the deflector system of a Pelton type.

According to the simulation results, the PSS-G has proven to be able to extend the operational range of generator side damping towards low frequencies and under poor grid conditions.

IX. Conclusion

The PSS-E and PSS-G could possibly complement each other to extend the overall oscillation frequency spectrum towards lower frequencies and high connection impedances of the generator. Oscillations with frequencies below 0.5 Hz could be better handled with the PSS-G under the mentioned grid conditions, depending on the respective actuator speed limits of the governor system. Thus, the ability of the governor system for damping improvement decreases at higher oscillation frequencies.

As seen from the simulations in time domain the governor system equipped with a PSS-G shows higher amplitudes of actuator excursions during the occurrence of oscillations compared to governors without PSS-G. The dimension of this additional stress for the mechanical system is determined by the number and duration of oscillation events. Therefore, the detailed investigation of the impact of the increased actuator movements on the mechanical and the hydraulic system is deemed necessary

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