DAMPING ENHANCEMENT BY ROBUST TUNING OF SVC CONTROLLERS IN THE PRESENCE OF LOAD PARAMETERS UNCERTAINTY

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Abstract

The paper explores the influence of power system loads on static VAr compensator (SVC) damping effectiveness. Equipped with properly tuned additional stabilizers SVCs have been successfully used for improving the damping of electromechanical oscillations in power system. The damping improvement is usually achieved through indirect voltage influence through voltage dependent loads. Tuning of an additional compensator stabilizer (ACS) traditionally assumes that loads are statically voltage dependent. However load parameters are generally uncertain and loads often exhibit some dynamic response. This uncertain dynamic behaviour of loads can introduce an additional phase shift between voltage and load response and such can detune the ACS. Examples of detuning effects of dynamic loads as well as robust tuning of ACS are presented and discussed.

1 Electromechanical oscillations

Modern electrical power systems are complex, generally consisting of a large number of different dynamic devices, including synchronous machines and loads. They are continually exposed to sudden small disturbances (and reasonably frequently to large disturbances) in load, generation and transmission network configuration.

Under such circumstances the appearance of oscillations in some part or between parts of the interconnected power system is a reasonably frequent phenomena. Oscillations can occur in interconnected power systems because of synchronous generators swinging against each other. These oscillation modes result from the rotors of machines, behaving as rigid bodies, oscillating with respect to one another, using the transmission system between the machines to exchange the oscillation energy [1]. Because the phenomenon involves mechanical oscillations of the rotor and oscillations of the generated electrical power, these oscillations are called electromechanical oscillations.

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They can be spontaneous, i.e., initiated by a small disturbance such as a change in load or generation, or by large disturbances, such as faults in a system. If they are unstable or poorly damped, they may even dominate the response of the system after about two or three seconds following the disturbance.

Sustained oscillations in the power system are highly undesirable. They can lead to fatigue of machine shafts, and can cause excessive wear of mechanical actuators of machine controllers. Also, oscillations make system operation more difficult. Their presence increases the risk of major system breakdown. Therefore it is desirable that oscillations are well damped. Unfortunately, as systems become more heavily loaded in response to economic and environmental pressures, damping tends to reduce.

1.1 Damping of oscillations

There is an enormous amount of work reported in this area. One of the pioneering works in the area [2] deals with the appropriate settings of excitation control parameters for improvement in damping and stability of synchronous generators. A wide range of power system devices is available or being considered as a method of damping oscillations. The most widely used are power system stabilizers (PSSs) [3, 4]. A PSS contributes to the damping of an inter-area mode largely by modulating the system loads[5]. If the voltage of the load bus is held constant, or the load does not vary with voltage, the effectiveness of the PSS drops significantly [5].

Excitation systems, governors and power system stabilizers are all installed locally within a power plant and used for improvement of power system response to small and large disturbances.

Apart from these, there are a number of flexible alternating current transmission system (FACTS) devices that have been extensively used in providing additional damping to power system oscillations in recent years. The advantage of these devices is that they can be placed at the most suitable locations in the system to achieve the desired goal of good damping. Controlled series compensators (CSCs) [6] are an example of those. Apart from extending the transient and steady state stability limits by increasing the transfer capabilities of the line and reducing the phase-shift between the sending and receiving ends [7], they have also been found to have significant effects on the damping of local and inter-area oscillations. Differently from static VAr compensators (SVC), location of CSCs were found to have almost no influence [6] on damping. Also CSCs always contribute to the positive damping of local and inter-area modes [8]. That is not always the case with SVCs. However a disadvantage of the use of CSCs is that they contribute to the appearance of sub-synchronous oscillations in the system.

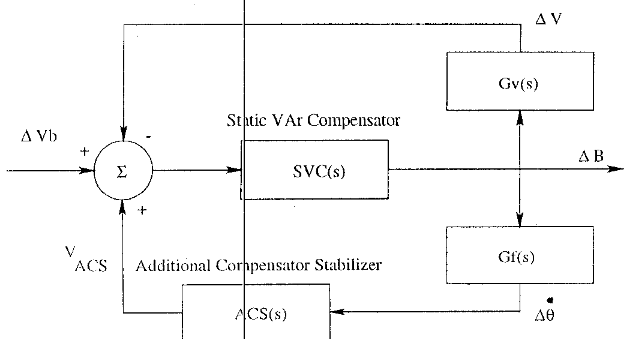

Figure 1: SVC block diagram representation

Static VAr compensators (SVCs) with additional damping signals in their voltage control loops [6, 9, 10], have also been extensively used for power system damping improvement. Damping control is achieved through a stabilizing loop. This is shown diagrammatically in Figure 1, where the stabilizer transfer function is given as $ACS(s)$. Their positive effects on damping are accomplished directly and indirectly. Direct effects are achieved by modulating the bus voltage to influence the power flow between machines. Indirectly, by modulating bus voltage they effectively modulate the voltage dependent load at the bus [8]. The additional signals that are generally used in damping controllers are rotor speed, bus frequency, derivative of power transfer through a line, as well as speed and frequency differences from remote locations [9]. (In this study bus frequency is used as an additional signal.) The stabilizer introduces some desired phase shift, with the phase shifted signal being added into the summing junction of the SVC's AVR. The stabilizer output signal causes fluctuations in the SVC susceptance, and hence in the bus voltage. If the stabilizer is tuned correctly, the voltage fluctuations act to modulate the power transfer level and the local load to damp modal oscillations. The best results in damping with SVCs have been achieved when they have been placed in the electrical midpoint between areas involved in oscillations. The effects on damping however, still depend on load conditions in the system [8].

1.2 Influence of power system loads

It can be noticed that for all devices so far used for the damping of electromechanical oscillations, the system loads play a significant role. In the oscillatory process that occurs in power systems, voltage dependent loads act as a source and sink of energy which is exchanged with the kinetic energy of the generators that are involved in the oscillations [5]. In fact, all these devices contribute to the enhancement of the damping of electromechanical oscillations by indirect control of voltage dependent loads in the power system.

As the voltage varies, real and reactive power also vary. The relationship between voltage and load has traditionally been modelled in the static form [11]. In this load representation, voltage and load are in phase. However loads often respond dynamically to voltage variations [12, 13]. This dynamic behaviour generally introduces a phase shift between voltage and load. This is explored in detail in [14]. There it is shown that the load provides a feedback path. Depending on load and system parameters, this feedback may improve damping. But a deterioration in damping is also possible.

The subject of this paper is the influence of loads and their parameter uncertainty on tuning of an SVC stabilizer. This problem has been initially addressed in [15]. The effectiveness of SVC damping control is due largely to forcing load variations to have a particular phase relationship with the inter-machine power oscillations. In [15] it is shown that if this phase shift due to the load dynamics is not taken into account when tuning the controls, the effectiveness of the SVC damping control could be significantly diminished.

In this study the problem of robust tuning of an additional SVC stabilizer (ACS) in the presence of uncertainty in load parameters is further explored.

2 Modelling of load uncertainty

In response to a step change in voltage, loads will generally undergo a step change in real and reactive power demand. The load will often then recover, over some time, to a steady state value which may be different to its pre-disturbance value. Important characteristics of this dynamic behaviour are the initial step change, the final value, and the rate of load recovery. A generic model which captures these characteristics (for non-oscillatory recovery) was proposed in [12]. For small disturbance studies of system damping, the model given in [12] is linearized in [14]. Linearization yields:

$$\Delta P_L = \frac{P_o}{V_o} n_{ps} \frac{(\frac{n_{pt}}{n_{ps}} T_p s + 1)}{(T_p s + 1)} \Delta V \tag{1}$$

$$\Delta Q_L = \frac{Q_o}{V_o} n_{qs} \frac{(\frac{n_{qt}}{n_{qs}} T_q s + 1)}{(T_q s + 1)} \Delta V \tag{2}$$

This linearized load model is incorporated in a linearized multi-machine power system model [16] in order to investigate machine and system damping and stability.

Parameters of the load model, active and reactive power time constant (T_p, T_q) and static and transient voltage exponents $(n_{ps}, n_{qs}, n_{pt}, n_{qt})$ depend on the type of load that is wished to be modelled. Different ranges of parameters were reported in the literature. They are summarized in [17]. Wide spread in the values of load parameters, even for similar types of loads, makes studies of general load influence very difficult. Further, there is always some uncertainty associated with load parameters due to difficulty of their determination [12]. The problem is overcame in this study by taking into account load parameter statistics. The approach used here is based on recently published results of measurement of load parameters [18]. It is shown in [18] that the load voltage exponents have a distribution that is close to normal within measured limits. The mean value of the distribution, i.e., the most probable value of voltage exponent, can however be located anywhere within that range. The mean values of distributions are different for different types of loads. This approach ensures the robustness of the results to parameter uncertainty.

The distributions of voltage exponents used in this study are shown in Figure 2. In the study it was assumed that voltage exponents $n_{ps}, n_{pt}, n_{qs}, n_{qt}$ vary randomly with normal distributions with mean values of $1.2, 2.4, 3$ and 6 respectively. As far as load time constants are concerned, they were assumed to have uniform distribution between $0s$ (which is an effectively static load) and $1s$ because this range has been determined as critical for the studies of power system damping [14, 16].

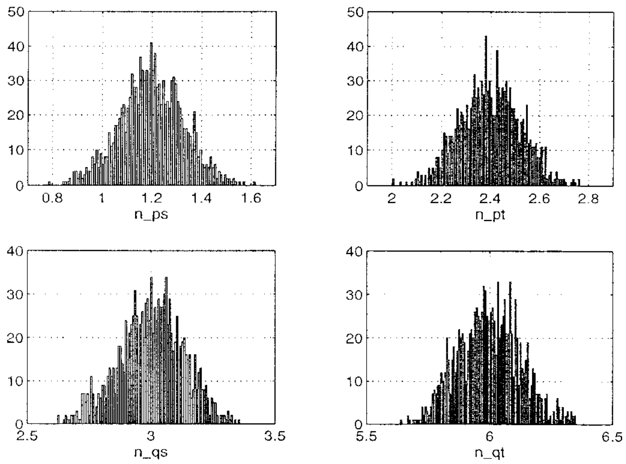

Figure 2: Normal distributions of load voltage exponents

3 Tuning of ACS

A transfer function residue based method given in [4] is used for tuning an additional compensator stabilizer (ACS). The procedure is based on the model given in Figure 1. Block $SVC(s)$ is the transfer function of the SVC, and block $ACS(s)$ is the compensator stabilizer. The block $G_v(s)$ models the response of the SVC bus voltage V to changes in SVC susceptance B. The block $G_f(s)$ models the response of the ACS input signal to changes in B. The dynamics of the power system (including load effects) are included in $G_v(s)$ and $G_f(s)$.

Bus frequency deviations $\Delta\dot{\theta}$ are used as the input to $ACS(s)$ block. This is an adequate choice for illustrating the effects of load dynamics. However the significance (or otherwise) of these effects is independent of the choice of input signal.

In tuning the ACS, the residue of open-loop transfer function $\frac{\Delta\dot{\theta}(s)}{\Delta V_b}$ is first determined. The transfer function of $ACS(s)$ block is then chosen to ensure that phase lead/lag of residue is fully compensated at the frequency of the corresponding electromechanical mode [4]. This is ideally achieved if the sum of the open-loop residue angle θ_R and phase shift through the $ACS(s)$ transfer function is equal to 180^o degrees [3, 4, 10]. In tuning $ACS(s)$ transfer function to produce desired phase compensation, sequential tuning has been applied [4]. The feasibility of $ACS(s)$ transfer function is assured by taking into consideration the fact that the phase shift of each lead/lag pair has to be approximately up to 60^o and that the number of lead/lag pairs should be between 1 and 4.

4 Case study

4.1 Tuning of ACS with static load at SVC bus

The example system used to illustrate the effects of load parameters on tuning of an additional SVC stabilizer is shown in Figure 3. It consisted of eight buses and is a rough equivalent (with preserved major oscillation modes) of a real power system. All loads in the example system were initially modelled by classical static load model with real power voltage exponent $n_{ps} = 1.2$ and reactive power voltage exponent $n_{qs} = 3$ as this is current practice used

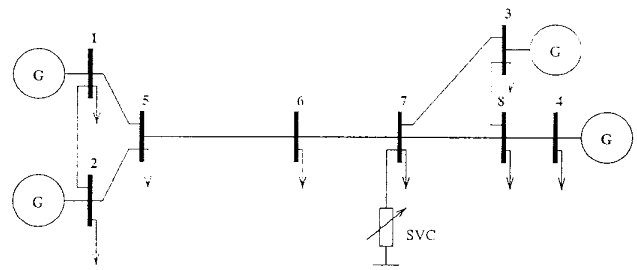

Figure 3: Four generator eight bus system studied

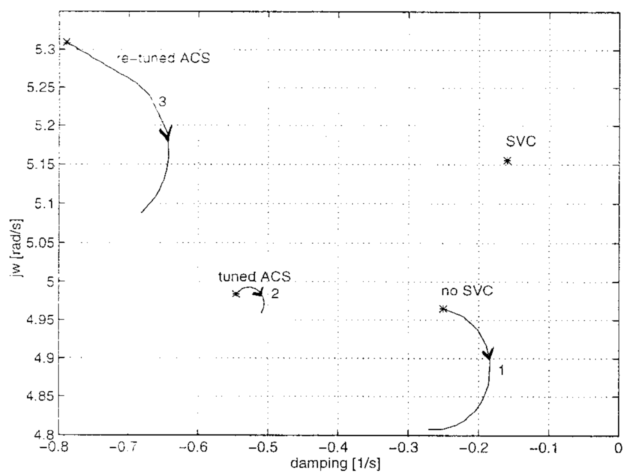

Figure 4: Effects of load dynamics, SVC and ACS on inter-area mode

in the original power system. After load flow analysis it was found that voltage at bus 7 was the lowest in the system and that by installing an SVC at bus 7 the level of transmission line voltages and load power factor will be increased. The system voltages and load power factor were of major concern at this stage, as it is often the case when deciding about an SVC installation.

Prior to installation of SVC two least damped electromechanical modes of the form $\lambda = \sigma \pm j\omega$ (where σ is damping in $[1/s]$ and ω is angular frequency in $[rad/s]$) were $\lambda_1 = -0.2504 \pm j4.9649$ and $\lambda_2 = -1.3890 \pm j10.4020$. Through calculation of participation factors of system state matrix it was found that mode λ_1 is an inter-area mode. It involves generators 2, 3 and 4. Mode λ_2 is found to be a local mode and it involves generators 3 and 4.

With an SVC at bus 7 the most critical mode, mode λ_1 became less damped than without SVC. This is illustrated in Figure 4. The new value of the least damped, inter-area mode. was $\lambda_1 = -0.1599 \pm j5.1554$. As it can be seen from Figure 4 the addition of an SVC in this case made system damping a little worse. Addition of the SVC at bus 7 effectively held the voltage at the bus constant. This in turn held the local voltage dependent loads constant. The natural load relief provided by the voltage dependence of the loads was lost, with a consequent reduction in system stability and damping. However, the placement of the SVC also had a positive effect: that of maintaining a consistently higher voltage (an average of 2.5%) on the interconnection between the two groups of machines. This strengthening of the system caused the increase in modal frequency observed in Figure 4. However because of relatively large amount of local load, the reduction in load relief was the dominant effect.

A procedure for tuning the stabilizing controls of an

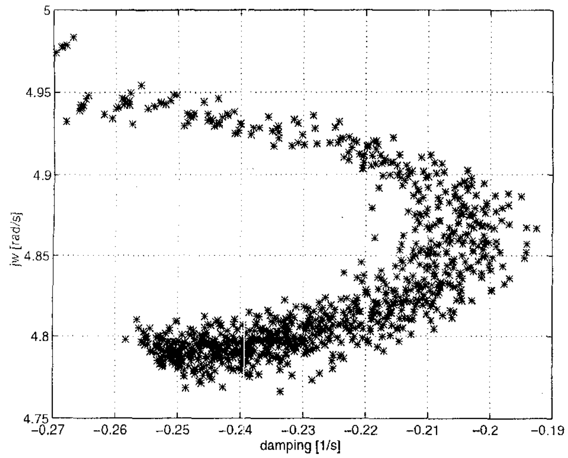

Figure 5: Effects of load parameters uncertainty on inter-area mode

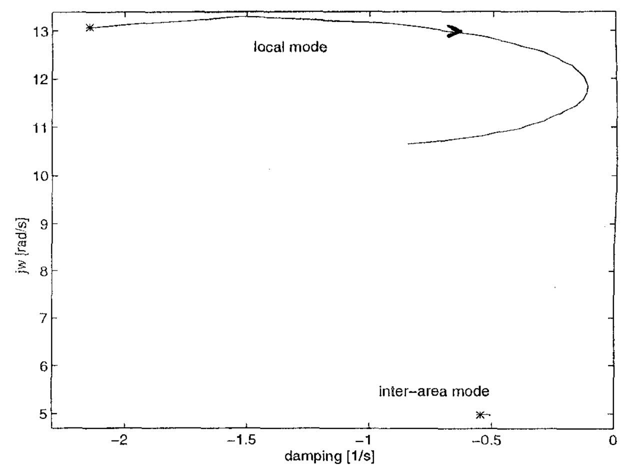

Figure 6: Effects of load dynamics on critical modes, with tuned ACS

SVC described in Section 3 was resumed. It was found that the angle of the residue of the transfer function $\frac{\Delta\theta(s)}{\Delta V_b}$ was $\theta_R = -149.41^o$. The additional system stabilizer (ACS) for an SVC was designed having in mind constrains mentioned in Section 3. The task was accomplished with an ACS with four lead-lag pairs. After additional tuning of the gain of ACS, the inter-area mode of the system was $\lambda_1 = -0.5456 \pm j4.9838$, and local mode, $\lambda_2 = -2.1460 \pm j13.0750$. With such tuned ACS, significant improvement in damping has been achieved for both modes. The initial task of improving interconnection voltage levels and subsequently system damping by adding an SVC with properly tuned ACS at critical bus might be considered accomplished.

4.2 Robust tuning of ACS with dynamic load at SVC bus

Previous studies have shown however, that voltage dependent loads can affect system damping [16] and tuning of SVC stabilizers [15]. In order to investigate the effects of uncertainty of load parameters on tuned ACS the following has been done.

Firstly the load at bus 7 was modelled by dynamic model as described in Section 2 without an SVC connected at bus 7.

Variation of inter-area mode damping and frequency with uncertainty in load parameters is shown in Figure 5. As far as the local mode (λ_2) is concerned, it was found that dynamic load at bus 7 has almost no influence at all on its damping and frequency. Considering initial results presented in [15], it was expected that dynamic load would have a significant effect on tuning of ACS.

Secondly, an SVC with previously tuned ACS (for static load at bus 7) is connected at bus 7. Load at bus 7 is modelled by a more deterministic model, i.e., voltage exponents were equal to mean values of normal distributions used previously in producing Figure 5 and time constants were varied from $0s$ to $1s$. This representation of dynamic load with uncertain parameters approximates observed mode behaviour shown in Figure 5 and is more convenient for this type of study than to use actual load parameter statistics [17]. The results obtained are shown in Figures 4 and 6.

Figure 4 shows that even with load at bus 7, modelled dynamically SVC with tuned ACS contributes to far better damping of inter-area mode (root locus 2 in Figure 4). The figure also shows that the inter-area mode damping is less sensitive to load dynamics than without SVC with ACS (smaller size of locus 2 than locus 1 in Figure 4). The load dynamics in this case didn't have a 'detuning' effect on ACS on damping inter-area mode as in the example shown in [15]. On the contrary, the system is virtually less sensitive to load dynamics. Considering these results based on initially least damped electromechanical mode (inter-area mode λ_1) one could conclude that with appropriately tuned ACS for local load modelled statically, a system will be far more stable with ACS than without it even when local load is modelled dynamically. With an appropriately tuned ACS, a system will also be less sensitive to load dynamics.

Consider now Figure 6. This figure shows variation of inter-area and local mode damping and frequency when load time constants vary from $0s$ to $1s$ with an SVC and tuned ACS. (In Figures 4 and 6, the first points of each of the loci (marked by an '*') indicate the initial position of the eigenvalue corresponding to the inter-area mode of the system. (These points were obtained using a static voltage dependent load model.) They also correspond to the situation where load dynamics are extremely fast, i.e., $T_p, T_q \to 0$. In that case, load is effectively static, with indices given by steady state characteristics n_{ps}, n_{qs} [16]. The loci correspond to increasing the load time constants T_p, T_q away from zero for the load at bus 7.) It can be seen not only that local mode is far more sensitive to load dynamics (larger size of its root locus) but also it becomes critical for system damping and stability for a range of load time constants (from $0.03s$ to $0.25s$). Recall that load dynamics didn't have any influence at all on local mode when SVC was not connected at bus 7. However load dynamics became critical for damping of this mode and it detuned the ACS. This resulted in the system being driven very close to stability limit. Such an influence of load dynamics on local mode can be explained by examining Bode plots of the system transfer function $\frac{\Delta\theta(s)}{\Delta V_b}$ shown in Figure 7. The dynamics of the power system (including dynamic load effects) are included in blocks G_v and G_f, and the dynamics of an SVC is included in block $SVC(s)$. From Bode plots shown in Figure 7 it can be seen that system is the most sensitive around local

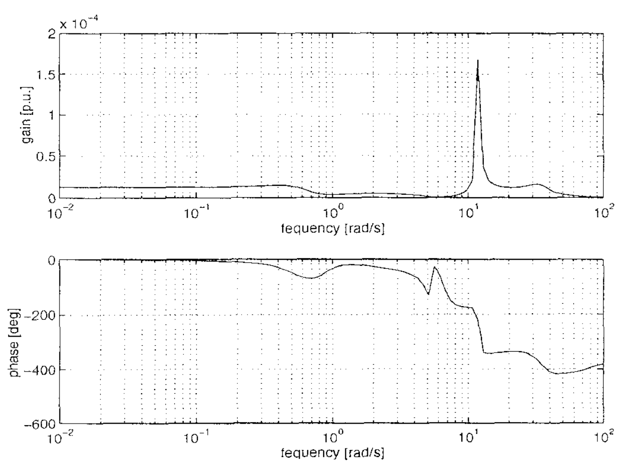

Figure 7: Bode diagrams of the system with an SVC and dynamic load at bus 7, as seen from the ACS

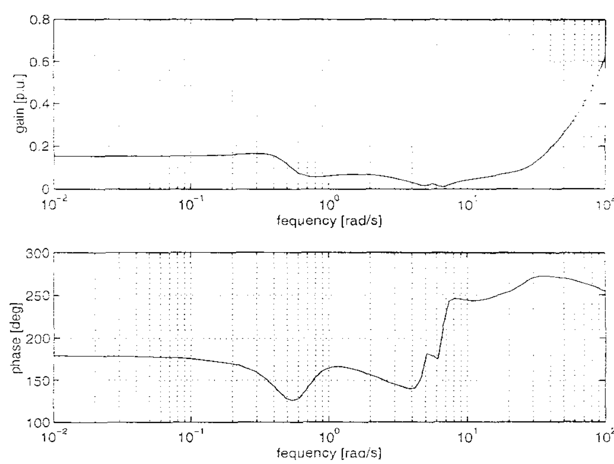

Figure 8: Bode diagrams of the system with SVC and re-tuned ACS, as seen from the load at bus 7

mode frequency (high peak at gain/frequency diagram), far more than around inter-area mode frequency. Also from the phase/frequency diagram it can be seen that at both modal frequencies the system experiences large, sharp changes in phase (again larger change around local mode frequency). As discussed in [14], gain and phase of the system transfer function are closely related to damping of the system's electromechanical oscillations. High gain and large, sharp change in phase shift of the open-loop system around local mode frequency, together with gain and phase shift of ACS introduced after closure of the feedback are the reasons for high sensitivity of local mode to load dynamics. Any change in load parameters will introduce change in gain and phase shift of the load transfer function [14] which in turn at local mode frequency will result in drastic changes of the gain and phase shift through the system.

The results presented in Figure 6 showed that ACS tuned to improve damping of the system, in fact contributed to its deterioration (in combination with dynamics of the local load). Further, they showed that the most affected oscillation mode, and the one which became critical for system damping and stability is not initially (with load modelled statically) less damped inter-area mode but initially far better damped local mode.

It is obvious that initial task of improvement of system damping with ACS has not been accomplished, having in mind load parameter uncertainties. Re-tuning of ACS is necessary. This time tuning should be done with regards to both, local and inter-area mode simultaneously. The ACS should be tuned to produce maximum damping at both critical modal frequencies.

It was found that with fixed voltage exponents of dynamic load as before, (mean values of normal distributions shown in Figure 2) inter-area mode is least damped ($\lambda_1 = -0.5056 + j4.9719$) for the load time constants of $0.5s$. Local mode however, becomes least damped ($\lambda_2 = -0.1173 + j11.8510$) for the load time constants of $0.07s$. Residues of open-loop transfer functions were calculated for both electromechanical modes at critical frequencies. It was found that with load time constants of $0.5s$ at 4.9719 rad/s the angle of the residue of transfer function $\frac{\Delta\theta(s)}{\Delta V_b}$ was $\theta_R = 154.41^o$. Required (ideal) angle compensation by ACS at this frequency for maximum damping improvement is 25.6^o. With load time constants of $0.07s$ and at a frequency of 11.851 rad/s the angle of the residue is $\theta_R = 102.92^o$. Therefore the required (ideal) angle compensation by ACS at this frequency for maximum damping improvement is 77.1^o [4]. The ACS is re-tuned in order to meet these requirements but the form and structure of ACS transfer function is preserved, i.e., the same number of lead-lag pairs as before is used. After re-tuning at 4.9719 rad/s, phase shift through the ACS transfer function was 29.5^o, and at 11.851 rad/s phase shift was 73^o. These were considered as sufficiently close to 'ideal' values determined before. Better agreement with 'ideal' values was not possible for the given form of ACS's transfer function, and it was necessary to preserve the form of ACS as it would be the case in 'real life' situation.

New values of inter-area and local mode under the same conditions as before (time constants of the local load $0.5s$ and $0.07s$ respectively) with re-tuned ACS were $\lambda_1 = -0.6492 + j5.1308$ and $\lambda_2 = -1.3160 + j10.3900$ respectively. Sensitivity to load dynamics is tested as before by varying load time constants from zero to $1s$. In this case it was found that local mode is again almost insensitive to load dynamics (as in the case without SVC and ACS). The inter-area mode however is more sensitive to load dynamics than with previously tuned ACS (compare the size of locus 3 and locus 2 in Figure 4) but still far better damped for all values of load time constants. This behaviour can be explained by inspecting Figure 8. In this figure, Bode plots of the transfer function of the system with SVC and re-tuned ACS are presented as seen from the load [16] at bus 7. It can be seen that the phase diagram is 'smooth' at both modal frequencies (especially at local mode frequency). The change in load phase shift [16] caused by variation of time constants, therefore will not have as significant an effect on damping as before.

4.3 Robustness of re-tuned ACS

A re-tuned ACS obviously provides very good damping of system's critical modes even when load dynamics is included. In order to check how robust the tuning of ACS is with respect to load parameter uncertainty, the following example was set. All eight loads in the example system were modelled dynamically. As before, it was assumed that all time constants vary randomly with uniform distribution between $0s$ and $1s$, and that all voltage expo-

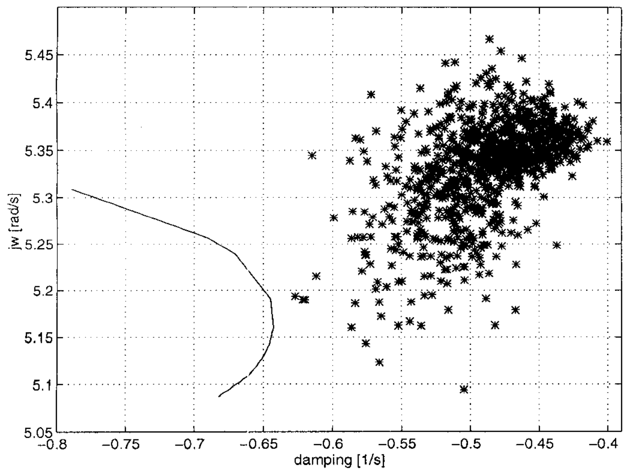

Figure 9: Damping and frequency of critical, inter-area mode for eight loads with uncertain parameters

nents vary randomly with normal distributions shown in Figure 2. The results obtained are shown in Figure 9. Root locus of inter-area mode shown in this figure is the same as locus 3 in Figure 4. It can be seen from Figure 9 that with all loads having uncertain parameters, the most critical mode (inter-area mode) is less damped than when only one load had uncertain parameters. (Local mode (λ_2) remains comparatively insensitive to load parameter uncertainty.) However a re-tuned ACS ensures that the system is still far better damped than when there was only an SVC without an ACS in the system or even when the system was without an SVC and with all loads modelled statically. This example shows the effectiveness of a properly tuned ACS in damping power system electromechanical oscillations even in the presence of uncertainty in load parameters.

5 Conclusions

This paper examines the influence of load parameter uncertainty on effectiveness of an additional SVC stabilizer for damping power system electromechanical oscillations.

It shows that if tuned to damp most critical mode in the system with loads modelled statically, an ACS may be detuned by load dynamics and contribute to worse damping of modal oscillations and reduced system stability.

The paper further shows that after additional robust tuning of an ACS it can provide far better damping of modal oscillations. Such robustly tuned ACS ensures better damping of system electromechanical oscillations even in the presence of uncertainty in load parameters.

The results presented emphasize the importance and capabilities of an SVC additional stabilizer in damping power system oscillations. However in tuning additional stabilizers, care must be taken with regards to load parameter uncertainty. Also an ACS should be tuned to provide adequate damping over a wider range of frequencies, not only at the frequency of initially least damped system mode.

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