# Impact of the Interaction Among Power System Controls
## Status Report of CIGRE TF 38.02.16


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***Abstract***

*CIGRE Task Force TF 38.02.16 on "Impact of the Interaction Among Power System Controls" was convened in 1997 to investigate the current status and promote the further development of the coordinated design of multiple controls in large power systems. Properly coordinated designs can mitigate possible adverse interactions among controls. Electromechanical and voltage problems will be studied, though the latter at a lesser extent. The task force report should be completed by mid or late 1999. Emphasis is on continuous, decentralized control, reflecting the industry practice and incorporating robustness issues to cater for multiple system scenarios. In order to provide guidelines, the taskforce will also study the interaction among continuous controls, discrete controls and protection.*



*Keywords: power system stability, coordinated control, control interactions, oscillations.*


## 1. Introduction

Unstable or poorly damped oscillations have been observed in the field or predicted by simulation tools in power systems around the world. A reliable computer simulation of these modes, regarding both damping and frequency, requires an extensive and detailed representation of the large interconnected systems [1].

The development of powerful eigenvalue programs for small-signal stability analysis has been, for some time, recommended by CIGRÉ [2]. Over the last two decades there has been intensive work on research and development in small signal stability analysis and linear control design tools for large scale power systems.

Among other valuable working group efforts, the CIGRE TF 38.01.07 concluded in 1996 an excellent report on "Control of Power System Oscillation" [3], describing the state-of-the-art in the area of improving damping of system oscillations with respect to: methods and means; practical experience; and analytical tools. The recommended system oscillations study procedure in [3] involves the use of small signal analysis complemented by nonlinear time-domain simulations. This procedure involves three steps:

1. Eigenvalue scan, to indicate the presence of poorly damped modes;
2. Detailed eigenanalysis of these modes to determine their nature and causes, and assist in developing damping controls;
3. Nonlinear time-domain simulations to confirm results of small-signal analysis and verify the impact of nonlinearities on damping.

The current taskforces CIGRE TF 38.02.16 “Impact of the Interaction Among Power System Controls” and CIGRE TF 38.02.17 “Advanced Angle Stability Controls” can be seen as a continuation of this effort. There will be not much overlap between these two task forces, since the latter is interested on new technologies for continuous and discrete supplementary stability controls. It will also focus on large disturbances and nonlinear aspects of stability control [4]. On the other hand, the focus of TF 38.02.16 will be given to methods and means for designing multiple controls while minimizing the adverse interactions among them. It will be control systems oriented containing brief mathematical descriptions of selected analysis tools and coordinated control design methodologies. Coordination here means the simultaneous tuning of the controllers to achieve a positive net improvement of the overall control scheme. The methodologies described must have been successfully employed in the design of multiple controllers for benchmark systems, the latter to be agreed upon by the TF members.

The addition of new damping sources together with more stressed operation in present interconnected power grids trigger the need for methods that can handle an overall coordination for the system controllers. Conventional design approaches, like the decoupled and sequential loop closure, cannot adequately handle interactions among controls. Properly coordinated designs can mitigate possible adverse interactions.

The current outline of the Technical Report for CIGRÉ TF 38.02.16 is as follows:

*1* - Introduction
*2* - Power System Controls
*3* - Possible Adverse Interactions in Controls and Protection
*4* - Analysis and Design Techniques
*5* - Computer Tools and Guidelines for Control Design
*6* - Suggested Performance Criteria Regarding Interactions
*7* - Conclusions
*8* - Summary
*Appendix 1* - Example System Models for Control Interaction Analysis and Design (Results and Data)
*Appendix 2* - Impact of Possible System Restructuring
*Appendix 3* - Overview of Numerical Algorithms for Small Signal Stability Analysis and Control Design

Despite the major algorithm and theoretical developments in the field, there is a pressing need for further research in controller design methods for large power system applications. The Task Force will identify some of the most fertile grounds for future research and development in this area. The operational aspects of the action of power system stabilizers is gaining increasing attention, so as to better coordinate them with generator protection and other controllers [5,6,7,8]. Aspects of interaction among continuous controls, discrete controls and protection will be also dealt with, so as to provide useful guidelines.

## 2. Power System Controls

In a power system, the main interactions among the system machines are strongly determined by their controls which are usually studied, designed and operated without the required level of coordination.

The control systems to this relevant analysis are:
- power plant level: excitation control, speed governor, reactive power control, tap-changer under load;
- network substation level: tap-changer under load, FACTS control, shunt reactor/capacitor banks switching, HVDC control, series capacitor control.
- power system level: power/frequency control, EHV network secondary voltage control.

In the final document, this chapter will be concerned with the description of these controls and the best known options for their structures and feedback signals.

Possible interactions among power system controls are of various types, this being the subject of the next section of this paper.

## 3. Possible Adverse Interactions in Controls

At the time of drafting this paper no clear definition of “interaction” as applied to power systems controls is agreed upon. One could consider a number of ways of classifying these interactions: frequency range, type of “interacting” medium, i.e. through the power system or through control signals, or a more phenomenological classification based on the types of controllers interacting and possible results of these interactions. In this section we have adopted the latter classification and different types of interactions are given below. The list below is not complete, other types of interactions are conceivable, but it covers most cases and the examples given here.

### *3.1. Different Types of Interactions*

3.1.1. Electromechanical: small disturbance

- *Interactions between PSSs*
- *Interactions between PSSs and FACTS Device Stabilizers*
- *Interaction between PSSs and Governors*
- *Interaction between PSSs and torsional modes*

The analysis of the above listed interactions benefit from the solidly established linear systems and control system theory. Modal Analysis and multivariable frequency domain approaches, among others, are adequate to study these interactions. A large dynamic coupling between two loops yields large off-diagonal terms in the associated transfer function matrix. An oscillatory mode mainly associated with this dynamic interaction has an associated transfer function residue matrix also having relatively large values in the same off-diagonal positions.

3.1.2. Electromechanical: large disturbance

At the same power plants:

- *Interaction between PSS and AVR during fault and in immediate post-fault period*
- *Interactions between under-excitation limiters and AVRs*
- *Interactions with load controls*

Among power plants:

- *Interaction among PSS and other controls*

3.1.3. Other types

- *SSR Problems*
- *Controls for voltage stability*
- *SVC controls*
- *HVDC Controls*

### *3.2. Examples of Interactions*

High coupling among controls usually means high electrical proximity and therefore high geographical proximity even if, in principle, the two proximity definitions are not always equivalent. Usually high concentration in a small area of loads and production determine high coupling and interaction with respect to situations having long distance links: in these terms interaction means electrical proximity.

Low interaction is also strongly linked with high dynamic decoupling such as, for example, between fast and slow modes.

This subsection provides examples of the types of interactions provided in the previous subsection.

3.2.1. Interactions between Stabilizers in Interconnected Power Systems

- *Interactions between PSSs*
- *Interactions between PSSs and FACTS Device Stabilizers*

The interactions discussed below are of an electromechanical nature and involve Power System Stabilizers (PSSs) and FACTS Device Stabilizers (FDSs). The interactions between PSSs and PSSs and between PSSs and FDSs are identified and quantified.

In an analysis, interactions may manifest themselves in a number of ways. For example, in determining the gain setting of a FDS using root-locus analysis it may happen that increasing the gain of the device improves the damping of one inter-area mode but degrades the damping of a second such mode. If PSSs determine the damping of the second mode, this could be interpreted as an interaction between the FDS and the PSSs. However, it is not possible using root-locus analysis to determine the reason for and nature of this interaction.

In the following, *in an attempt not only to explain the nature and significance of interactions between stabilizers but also to quantify them*, let us assume that

- the transfer functions of PSSs and FDSs are of the form $k_j.G_j(s)$,

- $G_j(s)$ of each stabilizer is designed to achieve a direct left-shift in the relevant modes of rotor oscillation, and
- $k_j$, the damping gain of the stabilizer, determines the extent of the left-shift.

With these assumptions, interactions can be related to the effects *of stabilizer gain changes only*, rather than parameter changes in the stabilizer transfer functions (i.e. time constants and gains).

The concept of damping and synchronizing torques acting on the shaft of a generator provides a basis for identifying interactions. This concept is related to that of a torque induced on the shaft of generator *i* by the "action" of the PSS installed on generator *j* - or through the "action" of FDS *j*. If the induced torque on generator *i* is in phase with speed on generator *i* , the torque is a damping torque. However, rather than consider induced torques, it is more convenient for a given mode of rotor oscillation $\lambda_h$ to deal with an induced torque *coefficient* $T_{ij}^h$ for generator *i*, i.e.

$$\Delta P_{ij}(\lambda_h) = T_{ij}^h \, . \, \Delta\omega_i(\lambda_h)$$

where $\Delta P_{ij}$ is the torque induced on generator *i* due to a perturbation in the input stabilizing signal on stabilizer *j* (a PSS or a FDS); $\Delta\omega_i$ is the associated perturbation in speed on generator *i*.

To illustrate the concept of an "interaction" let us consider an increment in gain on two stabilizers only, say, the PSS on generator *i* and PSS or FDS *j;* let's assume it is PSS *j*.

Consider mode $\lambda_h$. For an increment in the gain of stabilizer *j*, $\Delta k_j$, it can be shown that

- the increment in the induced torque coefficient $\Delta T_{ij}^h$ is proportional to $\Delta k_j$, and
- the associated contribution by generator *i* to the shift in the mode, $\lambda_h$, is given by

$$\Delta\lambda_{ij}^h = -(p_{ih} / 2 H_i) \Delta T_{ij}^h ,$$

where $p_{ih}$ is the complex speed participation of generator *i* in mode *h;* $H_i$ is the generator's inertia constant.

Let us examine the contribution to the shift in mode *h* by generator *i* for an increment $\Delta k_i$, in the gain of its *own* PSS, *i*. If the PSS is properly tuned, this contribution is

$$\Delta\lambda_{ii}^h = -(p_{ih} / 2 H_i) \Delta T_{ii}^h \approx -(p_{ih} / 2 H_i) \Delta k_i$$

The mode shift in the *s*-plane is directly to the left as the speed participation is predominantly real.

Due to the increments $\Delta k_i$ and $\Delta k_j$ in the gains (e.g. 1 pu on machine base), the contribution to the mode shift by generator *i* is

$$\Delta\lambda_i^h = -(p_{ih} / 2 H_i) \Delta k_i - (p_{ih} / 2 H_i) \Delta T_{ij}^h = -(p_{ih} / 2 H_i).[\Delta k_i + \alpha_{ij}(\lambda_h) \Delta k_j]$$

where $\alpha_{ij}(\lambda_h)$ is a complex number *. If both PSS gains are increased, it is apparent from the above equation that the gain increment $\Delta k_j$ can be considered to modify the effect of the gain increment $\Delta k_i$ on the damping of the mode; the effect, however, depends on the sign of the real part of $\alpha_{ij}(\lambda_h)$. For example, if the sign is negative, the gain increment on PSS *i* is not as effective as it is when the gain increment is made on PSS *i* alone. Consequently, from the point of view of adjustment to the gain settings, there appears to be an interaction between PSS *j* and PSS *i*.

The concept of interactions, or the associated torques on generators, help explain the role of PSSs and FDSs on the damping of local and inter-area modes of rotor oscillation.

(* There is of course a similar expression to latter equation for the contribution to the mode shift $\Delta\lambda_j^h$ for generator *j*.)

### 3.2.2. Interaction between the PSS and a Responsive Governor

• *Interaction between PSSs and Governors*

This is an illustrative example of interaction between a PSS and a responsive governor (however, this has not been proved) at Reece power station. Reece power station has 2 generators 120 MVA each. Two PSSs were commissioned at Reece power station in 1994. The PSSs are of electrical power input. The commissioning tests did not show any problems. The generators were on-line for several days and under different operating conditions, without any problems. Then, 5 days after commissioning, both generators tripped on field overexcitation current. Both machines were close to full output. Prior to the tripping Reece MVAr loading was becoming erratic and swinging between 5-45 MVAr and the system frequency was oscillating between 48 and 52 Hz. At that time there were no PMUs in the system so were left with no traces, therefore there was not enough information to start investigation why the incident happened. We suspect that there was interaction between the governors and PSS (which never showed up in computer simulations). Also, PSSs (being electrical power input) are very sensitive to power/frequency changes in the system, and it was noticed many times before that sustained frequency oscillations appeared in the system (these incidents initiated machine identification and governor retuning project), which may have triggered the incident. To avoid interaction we changed PSS output limiter to lower value and decreased the washout time constant from 3s to 1s. After these changes we did not experience the same problem again. However, low frequency oscillations (20s) were appearing in the system from time to time due to improperly tuned governors (performance is improving with every new governor retuned).

3.2.3. Interaction between Fast Acting Governors and PSS

- *Interaction between PSSs and Governors*

As was reported in the CIGRE TF 38.01.07 publication "Analysis and control of power system oscillations", we observed the interaction between the fast acting governors (needed because of our fluctuating load) and the electrical power input PSS at one of our power stations. This resulted in fairly large MVAr oscillations which were not considered acceptable. To overcome the problem the gain of the stabilizer was reduced substantially at low frequency (the frequency of the oscillation). This experience has been used in the selection of parameters for almost every other stabilizer on the Queensland system, with relatively low gains selected at the appropriate frequency. At the power station where the original interaction occurred, the compromise settings resulted in lower but still adequate damping. An alternative PSS with an accelerating power input was investigated and trialed on one unit. This overcame the interaction problem but was never implemented, mainly on economic grounds, as adequate damping (damping ratio of 0.05) was available with the compromise settings.

Another interaction we have observed during our selection of stabilizer settings is between the PSSs at Wivenhoe power station (a pump storage) and Tarong (thermal). The settings needed to be coordinated as particular settings at one could detract from the damping of modes between them. This was more of a design issue. Priority was given to setting the Tarong units first, as the Wivenhoe units are pump storage and therefore not on with stabilizing action all the time.

3.2.4. Interaction between the Automatic Voltage Regulators and the Under-Excitation Limiters at Mungarra in Western Australia

- *Interactions between under-excitation limiters and AVRs*

This is a brief summary of an unfavorable interaction that resulted in repetitive sustained voltage oscillations in a radial feeder with generation near the end of an electrically weak link. The oscillations occurred with the Mungarra GT sets at maximum output.

Phenomenon

In one incident voltage swings of -2.7% to +5.5% were recorded at Geraldton in Western Australia when the breaker was opened at the MUC end of the MUC-MOR 132kV line. Closing the breaker stopped the oscillations. The possibility of power system stabilizer & AVR interactions was considered but was considered unlikely so that attention turned to the possibility of under-excitation & AVR interaction.

It was observed that voltage instability (oscillations) occurred when the Mungarra gas turbine units were operating close to under-excitation limits. Instability was therefore suspected to arise from the dynamic interaction between these limiters and the network.

Analysis

Dynamic and small-signal eigenvalue analysis were used to work out stability limits and deduce a capability diagram of MW versus MVAr. This work showed that the units' stability is sensitive to network conditions e.g.: - operation is just inside the stable area of operation if all lines are in service and the generator loading is 36MW, -10MVAr (leading power factor) -

operation is just inside the stable area of operation if the MUC-MOR line is out of service and the generator loading is 36MW, +5MVAr (lagging power factor).

The under-excitation limiter (UEL) has a straight line characteristic. An incursion past the UEL line (i.e. in the direction lagging to leading/ -MVAr to +MVAr direction) causes an error signal to be generated and applied to the summing junction of the excitation control system where the terminal voltage error signal is also applied. This means that such incursions tend cause the compound voltage error + UEL error signal to boost terminal voltage and thus raise line voltage. When the incursion has ceased the total error signal is dominated by the voltage error signal not the UEL error signal so that normal AVR action resumes. Hence a cyclic swap between UEL error and AVR error signal results with the result that the 132kV line voltages oscillate up (UEL signal dominant) and down (voltage error signal dominant).

Solution, field tests, and operational experience

Detailed analysis is given in [63]. The paper shows that the solution was to reduce the UEL gain by a factor of four. It points out the desirability of using a proportional-integral type controller, to eliminate any steady state UEL error, rather than the (essentially) proportional type actually used. By adjusting the gain and time constant of the UEL a reasonable solution was found to the problem of voltage oscillations but at the expense of a slight generator terminal voltage rise.

The detailed analysis of the problem and its solution - the changing of UEL gain K and time constant T in the UEL block K/(1+Tp) - was confirmed by field tests. Since implementing changes to the UEL settings K and T the Mungarra units have been operating close to, into, and out of the UEL region without any voltage instability incidents.

### 3.2.5. Control Interactions in the New Zealand HVDC Link

• *HVDC Controls*

Incident

There is a HVDC between the North and South Islands of New Zealand. In December 1992, during commissioning tests on DC Reverse Power flow i.e. from North Island to South Island, a 2 Hz oscillation was observed. It was initiated by a fault on the 220 kV bus at the Benmore inverter end. The operating power level was 600 MW. It was suspected that any power level higher than 400 MW is thus prone to this instability.

Cause

The 2 Hz is a dominant frequency of oscillation of the synchronous condensers against the rest of the North Island. During reverse power operation, it was also found that the amount of damping is dependent on the level of power transfer and the frequency stabilizer response.

Reproduction

At 600 MW south the oscillation was reproduced by applying a single phase to ground fault at Benmore end. Initial transient stability studies with **Prony Analysis** have suggested that the frequency stabilizer lag time constant be reduced to 22ms from 100ms to improve the damping. And this was introduced at site. The simulator exercise was to verify that the change had improved damping for the 2 Hz oscillation.

To see the effect of the frequency stabilizer (FS) during the transient recovery it was initially turned off. This showed very good improvement in damping at every power level. By modifying the frequency stabilizer parameters it was possible to improve the damping.

Damping Levels

With the 100 ms FS lag time constant it was found to be unstable on the simulator, although the commissioning results showed reasonable damping. This could be attributed to the stronger ac system conditions during the commissioning tests. The 22ms change avoids the 2 Hz instability and settles down in 3-4 seconds.

Tests at 400 MW and 800 MW the damping was found to be higher than at 600 MW reverse power transfer. Therefore it appears the 800 MW south power was not a problem as expected.

Effect of this Change on North Power Operation

The effect of these changes was tested at high power in the forward direction i.e. from South to North, and found to have good damping.

Further tests indicated that this change contributed to the 7-10 Hz oscillations when in minimum area firing condition. Therefore the frequency stabilizer time constants are now switched depending on the power flow direction.

### 3.2.6. Interactions in Multi-Infeed HVDC Systems

• *HVDC Controls*

General

Since HVDC links are becoming more common in the power systems the possibility of more than one HVDC link in the system must often be considered. A situation with two ore more HVDC links electrically close to each other is often referred to as a multi-infeed HVDC system. (They are called multi-*infeed* because the worst interactions occur if the converters are inverters, thus feeding power into the system.) Examples of power systems having multi-infeed HVDC configurations are Scandinavian power system and the Indian one. In the systems mentioned above the multi-infeed configuration had to be taken into account when designing the new HVDC converters and their controls.

Phenomenon

An HVDC link is asynchronous, i.e. its operation is independent on the phase angles of the system, and the interaction between nearby HVDC links is thus constituted by the voltage magnitude at the converter buses. That means that this type of interaction is very much coupled to the reactive power balance and voltage coupling between the HVDC systems. A typical interaction could be as follows: One HVDC link is ordered to increase its power level by one of its controllers. This results in a sudden voltage decrease at the inverter bus due to the increased reactive power consumption of the converter. This voltage decrease is then experienced at the converter bus(es) of nearby HVDC links, and if these voltage changes are too large, or too rapid, that might cause improper operation of these HVDC links, e.g. commutation failures. Another critical situation could occur after a fault when the HVDC links should recover and take up load again. Load recovery often implies increased reactive power consumption, and severe voltage depressions could result if no coordination is employed.

Obviously the strength of the power systems, i.e. the short circuit capacity, and the coupling impedance between the HVDC stations are key parameters when determining the severity of the interactions.

The interactions described above are the most fundamental ones and is directly coupled to the basic function of the HVDC link. Other types of interactions that could occur are harmonic interactions, and interactions through the control and protections, but these types of interactions are not specific for multi-infeed HVDC systems.

Remedies

To cope with the above problems a study including all the interacting HVDC links must be done. An example of such a study is reported in [61]. This reference reports from a study made of the Scandinavian system and a number of different study tools were used. To cope with possible adverse interactions coordination between the HVDC controls is the most cost effective solution. Such a coordination could imply that one of the converters should be equipped with voltage stabilizing controls, which might imply a slightly higher cost of the converters. Other actions might be to coordinate the recovery of the converters after a fault in such a way that they do not pick up load at the same time but rather with different time constants, so called staggered recovery. In extreme cases installation of SVCs and other voltage supporting equipment might be needed.

Because of the complexity of the problem it is not possible to give more general guidelines, but each specific system must be studied to identify the best solution.

Study tools

A number of different tools and methods have been used to study multi-infeed systems. As described above the basic phenomenon is very much coupled to the reactive power and voltage stability of the power system. Therefore many of the tools used for voltage stability analysis could be used provided the HVDC links and their controls could be modeled appropriately. A method using eigenvalues of a quasi-steady state Jacobian is reported in [62]. This method could be used to identify possible problems at an early stage in a planning process. One can also use his method to identify the most effective location of voltage support either by modification of HVDC controls or installation of e.g. SVC.

In [61] the use of HVDC real-time simulators and time domain simulation programs, i.e. EMTDC, is demonstrated for multi-infeed HVDC systems. The method of [62] is also used in the study of the Scandinavian system in [61].

## 4. Analysis and Design Techniques

The design of multiple power system controllers demands that several specifications be fulfilled in order to ensure the system operation with adequate margins for a multitude of operating conditions. The coordination as a design requirement has not been emphasized by the industry in the case of PSSs, since

- a suitable technique which permits simultaneous coordination of stabilizers has not been available,
- a direct method is employed for determining systematically the time constants in the PSS transfer functions in multimachine systems, however, the PSS gains are not set on a coordinated basis,
- a sequential approach based on a machine-infinite bus model coupled with classical control tools may suffice in most cases.

In the case of FACTS devices, the more conventional approach to power system controllers design is much more limited. Many design methods for these devices rely on tentative parameter tuning using simulations to evaluate the design. The likely increase on the number of controlled devices in tomorrow's power systems will require a more systematic design procedure. The coordination of these controllers is necessary to optimize the performance and to avoid adverse interaction among different controllers.

The issues of control coordination, controller siting and feedback signal selection play an important role in mitigating control interactions. New design techniques that take into account simultaneous tuning of multiple controllers should be aimed for. The feedback signals must have high observability to the modes of interest in various system operating conditions. Signals should be chosen such that high frequency interactions be avoided. The controllability of an equipment to certain dynamics is closely related to its location on the system, and therefore a proper controller siting will greatly ease the control synthesis problem.

Appendix A provides a background on system modeling with adopted mathematical notation, used to describe the various methods in this section.

### *4.1. Heuristic and Linear Programming Methods*

In this contribution it is shown that interactions occur between stabilizers in multimachine power systems; these stabilizers may be Power System Stabilizers (PSSs) or FACTS device stabilizers (FDSs). The interactions, which are identified and quantified, may enhance or degrade the damping of certain modes of rotor oscillation. In particular, interactions between PSSs may degrade the damping of inter-area modes. However, the damping of the latter modes can be significantly improved by the use of stabilizers installed on FACTS devices. In particular, the analysis of interactions also provides both a means for assessing the *relative effectiveness* of stabilizers and a method for the *systematic coordination* among PSSs and also among PSSs and FDSs. It is shown that such coordination of stabilizers provides a means of selecting all the parameters of stabilizers on a proper engineering basis such that the damping of rotor modes satisfy specified criteria.

The method has the following features:

- the transfer functions of both PSSs and FDSs are of the form $[k_j.G_j(s)]$,
- The transfer function $G_j(s)$ of each stabilizer is of the form

$$K_o.(s+ ...b_m.s^m) / (1+a_1.s+ ...a_n.s^n),\ m \leq n,$$

and is designed to achieve a left-shift in the relevant modes of rotor oscillation;

- $k_j$, the damping gain of the stabilizer, referred to as its 'gain', determines the extent of the left-shift.

The advantage of the above form of the stabilizer TF is that interactions can be related to the effects *of stabilizer gain changes only*, rather than parameter changes in the stabilizer TF. Moreover the coordination between PSSs and between PSSs and FDSs then becomes a task of coordinating their gains, as described below.

The purpose of coordination of stabilizers is to ensure that the specified damping criteria for the rotor modes are achieved. The procedure for coordination employs the stabilizer damping contribution diagram (which provides significant physical insight to the user) as the basis for determining the gain settings of selected (or all) FDSs and PSSs. This procedure uses either a heuristic approach or linear programming to satisfy the specified criteria. The former method is applicable in simple cases involving few stabilizers, operating conditions and modes. With more complex cases, however, an automated process employing linear programming is used to satisfy some objective function, e.g. minimize a weighted function of stabilizer gains over a range of rotor modes. The software displays the results as the computation proceeds so that a controlled, "hands-on" environment is created for the user.

The size of system is not limited by QR eigenanalysis. References [21,22,23,24], [25] and [26,28,29,30] cover PSS design, FDS design, and their coordination, respectively.

### *4.2. Iterative Pole-Placement Method*

The pole placement method described below is based on the algorithm originally proposed in [9], which has been extended and applied to the coordinated design of PSSs and the supplementary controls of FACTS devices [10].

The method under consideration is an iterative procedure which sequentially performs the tuning of the controllers, taking into account, at each stage, the dynamical interactions with the remaining machines and controllers. Suppose that, at a given stage, the controller for device *i* is to be tuned. Considering that the controller transfer function has the structure shown in Eq. (A.10), the characteristic equation for the closed loop system is:

$$1 - F(s)G(s) = 0 \qquad (1)$$

Let $\lambda$ be a specified location for a pole of the closed loop system. Denoting by $e + jf$ the value of $F(\lambda)$, one obtains from Eq. (1):

$$e + jf = \frac{1}{G(\lambda)} \qquad (2)$$

in which G(s) is given by Eq. (A.7). The parameters of the controller structure given by Eq. (A.10) are computed by comparing with Eq. (2).

This procedure is repeated for each controller whose parameters are to be tuned. An iteration is completed when all controllers have been re-adjusted. The convergence criterion is satisfied when the largest absolute deviation between the eigenvalues assigned in iteration *l* and those allocated in iteration *l*-1 becomes less than a pre-specified tolerance.

This method can be applied to large systems, since sparsity can be exploited in the solution of Eq. (2).

### *4.3. An Optimal Control Method*

In the last decade new methods and tools for optimal controller design applicable to large scale systems have been developed [11,12,13]. Some of these methods take into account the existence of practical structural constraints to be imposed on the resulting control strategy. Of particular interest are constraints such as decentralization and feedback of only those variables which are measurable.

Eq. (A.13) can be written as:

$$\dot{\mathbf{x}}_a = (\mathbf{A}_a - \mathbf{B}_a \mathbf{G}_a \mathbf{C}_a)\mathbf{x}_a \qquad (3)$$

where, $\mathbf{x}_a \overset{\Delta}{=} [\mathbf{x}^T, \mathbf{x}_c^T]^T$ and

$$\mathbf{A_a} = \begin{bmatrix} \mathbf{A} & \mathbf{BC_c} \\ \mathbf{0} & \mathbf{A_c} \end{bmatrix}; \qquad \mathbf{B_a} = \begin{bmatrix} \mathbf{B} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix}; \quad (4)$$

$$\mathbf{C_a} = [\mathbf{C} \quad \mathbf{0}]; \quad \mathbf{G_a^T} = [-\mathbf{D_c^T} \quad -\mathbf{B_c^T}] \qquad (5)$$

Using an adequate state space representation of the type given by Eqs. (A.11)-(A.12) for the controllers and assuming $T_2$ and $T_4$ known, matrices $\mathbf{A}_a$, $\mathbf{B}_a$ and $\mathbf{C}_a$ become completely known, and the controller unknown parameters appear only in matrix $\mathbf{G}_a$. It is verified that Eq. (3) exhibits the form of a *constant output feedback problem* $\mathbf{u}_a = -\mathbf{G}_a \mathbf{y}_a$, where the (fictitious) process to be compensated is described by matrices $\mathbf{A}_a$, $\mathbf{B}_a$ and $\mathbf{C}_a$, $\mathbf{G}_a$ is a constant output feedback matrix to be determined and $\mathbf{y}_a = \mathbf{C}_a \mathbf{x}_a$. This problem can be solved by a structurally constrained optimal problem [11]. Such problem consists in determining a control strategy that minimizes a quadratic performance index (Linear Regulator Problem-LQR):

$$J(\mathbf{x}_a, \mathbf{u}_a) = \frac{1}{2}\int_0^{\infty} (\mathbf{x}_a^T \mathbf{Q} \mathbf{x}_a + \mathbf{u}_a^T \mathbf{R} \mathbf{u}_a) dt \quad (6)$$

where the semi-definite positive matrix **Q** and the positive definite matrix **R** are weighting matrices. The constraints on the gain matrix can be represented by **F(K)** = 0, where the function **F** is determined by the nature of the restriction (decentralized state feedback, output feedback or decentralized output feedback).

The solution of the structurally constrained optimal control problem is obtained through the *Generalized Riccati Equation* [12]:

$$\mathbf{A}_a^T \mathbf{P} + \mathbf{P}\mathbf{A}_a - \mathbf{P}\mathbf{B}_a \mathbf{R}^{-1} \mathbf{B}_a^T \mathbf{P} + \mathbf{Q} + \mathbf{L}^T \mathbf{R} \mathbf{L} = \mathbf{0} \quad (7)$$

where **L** is a matrix which is used to “drive” the solution so that the structural constraints are satisfied. The imposition of the structural constraints imply a deviation from the optimal solution obtained from the unconstrained problem.

A general algorithm to handle *LQR* problems with structural constraints is presented in [13]. This algorithm furnishes a result that is used to determine the gain matrices $\mathbf{G}_{ai}$ that feedback the output. From this latter matrix the controller supplementary parameters can be obtained. In [13] the structurally constrained optimal control is solved by using the Chandrasekhar equations, allowing that sparsity be exploited and therefore the application to large systems.

### *4.4. Projective Controls Method*

The objective of the control design method summarized in this section is to coordinate two or more measurements with two or more control signals, to produce a better system dynamic performance than the performance obtained using a single measurement and a single control signal. The method is the projective controls approach presented in [47,48]. In this approach, a set of dominant dynamic characteristics of a full state feedback system are mapped into a much simpler output feedback system. This mapping is often accomplished with a low order feedback matrix which coordinates selected control and measurement signals.

The foundation of the coordinated control design is the well-known linear quadratic regulator problem

$$\min \frac{1}{2}\int_0^{\infty} (\mathbf{x}^T \mathbf{Q} \mathbf{x} + \mathbf{u}^T \mathbf{R} \mathbf{u})\, dt \qquad (8)$$

subject to

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \\ \mathbf{y} &= \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u} \end{aligned} \qquad (9)$$

The solution to this problem is a full-state feedback controller, where the closed loop system is given by

$$\dot{\mathbf{x}} = (\mathbf{A} - \mathbf{B}\mathbf{G})\mathbf{x} \qquad (10)$$

the feedback matrix $\boldsymbol{G}$ is

$$\boldsymbol{G} = \boldsymbol{R}^{-1} \boldsymbol{B}^T \boldsymbol{M} \qquad (11)$$

$\boldsymbol{M}$ is the non-negative definite solution of the matrix Ricatti equation

$$\boldsymbol{A}^T \boldsymbol{M} + \boldsymbol{M}\boldsymbol{A} - \boldsymbol{M}\boldsymbol{B}\boldsymbol{R}^{-1}\boldsymbol{B}^T\boldsymbol{M} + \boldsymbol{Q} = \boldsymbol{0} \qquad (12)$$

Once $\boldsymbol{M}$ has been computed, the method described in [47,48] is used to map the full-state feedback controller into an output feedback controller of the form

$$\boldsymbol{u} = \boldsymbol{K}\boldsymbol{y} \qquad (13)$$

The output feedback system retains *r* eigenvalues and their associated eigenvectors from the full-state feedback solution. The number of eigenvalues and eigenvectors retained (*r*), is equal to the number of independent measurements. The feedback matrix $\boldsymbol{K}$ is given by

$$\boldsymbol{K} = -\boldsymbol{R}^{-1} \boldsymbol{B}^T \boldsymbol{M} \boldsymbol{X}_r (\boldsymbol{C}\boldsymbol{X}_r)^{-1} \qquad (14)$$

In Eq. (14), $\boldsymbol{X}_r$ is the matrix of *r* eigenvectors retained. The output feedback system is given by

$$\dot{\mathbf{x}} = (\mathbf{A} - \mathbf{B}\mathbf{K}\mathbf{C})\mathbf{x} \qquad (15)$$

The application of the control design process described above to several power system and power plant applications are documented in References [40,41,42,43,44,45,46,47]. These applications include the design of a system-wide damping controller in a power system with more than 100 generators [41], and the coordination of the control action of a Thyristor Controlled Series Capacitor (TCSC) and a Thyristor Controlled Phase Angle Regulator (TCPAR), to allow for increased power transfers with improved system damping, using two measurements and two control signals [40].

### *4.5. Genetic Algorithm Approach*

GAs are search procedures based on the mechanics of natural selection and genetics. They were developed to allow computers to evolve solutions to difficult problems, such as function optimization and artificial intelligence. The basic operation of a GA is conceptually simple: maintain a population of solutions to a problem, select the better solutions for recombination with each other, and use their offspring to replace poorer solutions. Recently, GAs have been gaining attention in the power engineering community as an increasing number of related work is being published.

Similar in principles to the works presented in [13,26], this approach consists of a highly flexible linear control design method, which takes advantage of the simplicity of GAs. Usual concerns in optimization problems such as non-differentiability, non-linearity and non-convexity do not limit the use of this search method.

The method is based on the optimization of a non-explicit function, related to the damping ratios for the whole closed-loop pole spectrum, over the controller parameter space. The damping controllers are assumed to be of a fixed conventional structure, consisting basically of lead-lag filters. The robustness of the controllers is taken into account during the tuning process simply by considering a pre-specified set of system operating conditions into the objective function [38].

In addition to the constraints on the parameter bounds, the GA-based optimization problem can readily accomplish control performance constraints, such as required minimum damping for the closed-loop poles. A decentralized coordinated design is performed simultaneously where each damping controller is only derived from local variables.

Advancements in computer technology are making possible the solution of large problems such as this GA application. The GA tuning method mentioned here, was already tested in a large-size power system (a 1762-bus modified equivalent South-Southeastern Brazilian System) with the objective to coordinate 22 PSSs considering three loading scenarios. Affordable computation time was verified for the Brazilian system, where most of the CPU time is spent in solving multiple eigensolutions in a system matrix of about 500 states by the QR algorithm [39].

## 5. Computer Tools and Guidelines for Control Design

The objective of this task is to describe practical software tools for the coordinated design of controllers and for the analysis of interactions among controllers. These tools include software packages based on well established techniques, as well as programs based on relatively new methods.

The CIGRE report on “Control of System Oscillation”, published in 1996, contains an Appendix with brief descriptions of available software packages for small signal stability analysis and control design. The current CIGRE TF 38.02.16 is expected to delve into the coordinated design functions available in these packages. The taskforce will also promote the further development of advanced computer tools for multiple control design in large-scale systems. Computer algorithms that consider mode dominance, sparsity and friendly graphical user interfaces (GUI) are most appealing.

Modern control techniques in many cases are not suited to large-scale systems owing to the computational burden usually involved on those techniques. The methods of model-order reduction and mode dominance will make the application of mathematically sound techniques possible. Program packages, such as MATLAB, have many new control techniques that can be readily used, however they have the limitation of handling only small systems. A combination of programs could end up giving powerful design tools.

## 6. Concluding Remarks

The first draft of the taskforce report will be ready by July 1998, in time to be discussed during the CIGRE Paris meeting.

An appendix of the document contains a detailed description of the recommended numerical algorithms for small signal stability analysis and control design. The emphasis is on matrix sparsity preserving algorithms, meant for use in large scale system models.

The current draft of the document is still quite embrionary, and some parts need a lot of editing to turn the various individual contributions into a single, consistent text.

Modern power systems are increasingly benefiting from FACTS technology. These new devices provide greater flexibility at the expense of more complex control requirements. Our job as dynamics and controls engineers is to take advantage of the degrees of freedom gained with these new control devices, while reducing possible adverse interactions among them.

The current members accumulate a vast knowledge in the subject of this taskforce. There are, therefore, high expectations that the resulting work will be of practical value to industry.


## Acknowledgements

CIGRE work is largely based on volunteer work. The authors therefore thank the taskforce members and other contributors, as well as their companies, for their support in the preparation of this document.


## 7. References


[1] **P. Kundur,** "Power System Stability and Control", *McGraw-Hill*, 1994.

[2] **C. Barbier, E. Ferrari and K. Johansson**, "Questionnaire on Electromechanical Oscillation Damping in Power Systems - Report on the Answers", *Electra*, No. 64, pp. 59-90, 1979.

[3] **CIGRÉ TF 38.01.07**, "Analysis and Control of Power System Oscillations", *Brochure 111*, December 1996.

[4] **C.W. Taylor**, "Survey of Advanced Angle Stability Control: progress report on behalf of CIGRE TF 38.02.17", *invited paper for VI Symposium of Specialists in Electric Operational and Expansion Planning (VI SEPOPE)*, Salvador, Brazil, May 24-29, 1998.

[5] **A. J. P. Ramos, L. R. Lins, E. H. D. Fittipaldi and L. Monteath**, "Performance of Under Excitation Limiter of Synchronous Machines for System Critical Disturbances", *IEEE Trans. on Power Systems*, Vol. 12, No. 4, Nov. 1997, pp. 1702-1707.

[6] **J. M. Soares, et. al.**, "Operational Aspects of the Actuation of Power Systems Stabilizers: Coordination with Protection and Other Controllers", *Proc. V SEPOPE*, Recife, PE, May 1996.

[7] **J. R. Ribeiro**, "Minimum Excitation Limiter Effects on Generator Response to System Disturbances", *IEEE Trans. on Energy Conversion*, Vol. 6, No. 1, March 1991.

[8] **M. Klein, G. J. Rogers, S. Moorty and P. Kundur**, "Analytical Investigation of Factors Influencing Power System Stabilizers Performance", *IEEE Trans. on Energy Conversion*, Vol. 7, No. 3, Sep. 1992.

[9] **S. Elangovan and C. M. Lim**, "Efficient pole-assignment method for designing stabilizers in multimachine power systems", *IEE Proceedings*, 134(6):383-384, November 1987.

[10] **F. D. Freitas, A. S. e Silva, and A. J. A. Simões Costa**, "Coordinated setting of stabilizers for synchronous generators and FACTS devices in power systems", in *CIGRÉ Symposium on Power Electronics in Electric Power Systems*, Tokyo, Japan, May 1995.

[11] **J. C. Geromel**, "Methods and Techniques for Decentralized Control System: Analysis and Design", *Ed. Clup, Milano*, Italy, 1987.

[12] **I. Petersen and C. Hollot**, "A Riccati equation approach to the stabilization of uncertain linear systems", *Automatica*, 22(4):397-411, 1986.

[13] **A. J. A. Simões Costa, F. D. Freitas, and A. S. e Silva**, "Design of decentralized controllers for large power systems considering sparsity", *IEEE Trans. On Power Systems*, 12:144-152, February 1997.

[14] **W. E. Schmitendorf**, "Designing stabilizing controllers for uncertain systems using the Riccati equation approach", *IEEE Trans. on Automatic Control*, 33(4):376-379, 1988.

[15] **O. I. Kosmidou, H. Abou-Kandil, and P. Bertrand**, "A game theoretic approach for guaranteed cost control", in *EEC91 - European Control Conference*, pages 2220-2225, Grenoble, France, 1991.

[16] **A. S. Bazanella, A Fischman, A. S. e Silva, J. M. Dion, and L. Dugard**, "Coordinated robust controllers in power systems", in *Stockholm Power Tech*, page, Stockholm, Sweden, June 1995.

[17] **A. S. Bazanella, A Fischman, A. S. e Silva, J. M. Dion, and L. Dugard**, "Application of Linear Matrix Inequalities Techniques to the Design of Robust Coordinated Controllers for Power Systems", in *IFAC Third Conference on System Structure and Control*, Bucharest, October 1997.

[18] **F.P. de Mello and C. Concordia**, "Concepts of synchronous machine stability as affected by excitation control", *IEEE Trans. PAS*, pp. 316-329, 1969.

[19] **E.V. Larsen and D.A. Swann**, "Applying power system stabilizers: Part I-III", *IEEE Trans. PAS*, pp. 3017-3046, 1981.

[20] **P. Kundur, M. Klein, G.J. Rogers and M.S. Zywno**, "Application of power system stabilizers for enhancement of overall stability", *IEEE Trans. PWRS*, pp. 614-626, 1989.

[21] **M.J. Gibbard**, "Coordination of multi-machine stabilizer gain settings for a specified level of system damping performance". *Proc. IEE*, Pt. C, Vol.129, No.2, pp.45-48,1988.

[22] **M.J. Gibbard**, "Robust design of fixed-parameter power system stabilizers over a wide range of operating conditions". *IEEE Trans.PWRS*, Vol. 6, No. 2, pp. 794-800, 1991.

[23] **B.R. Korte**, "Application of power system stabilizers for the South Australian inter-connection", *Proc. of International Power Engineering Conference*, IPEC'93, Singapore, 18-19 March, pp.398-403, 1993.

[24] **D.M. Lam and H. Yee**, "A study of frequency responses of generator electrical torques for power system stabilizer design", *accepted for publication in IEEE Trans*actions.

[25] **P. Pourbeik and M.J. Gibbard**, "Damping and synchronizing torques induced on generators by FACTS stabilizers in multimachine power systems", *IEEE Trans. PWRS*, *Vol 11, no. 4*, Nov 1996, pp. 1920-1925.

[26] **P. Pourbeik and M.J. Gibbard**, "Simultaneous coordination of Power-System Stabilizers and FACTS device stabilizers in a multimachine power system for enhancing dynamic performance", *Paper no. WM97-171, IEEE Power Engineering Society Winter Meeting*, New York, 2-6 Feb 1997.

[27] **D.R. Ostojic**, "Identification of optimum site for power system stabilizer applications", *IEE-Proceedings*, Pt. C, pp. 416-419, 1988.

[28] **D. Vowles, P. Pourbeik and M.J. Gibbard**, "Contribution of individual PSSs and FACTS device stabilizers to the damping of rotor modes of oscillation", *Proc. of the International Power Engineering Conference*, IPEC'97, Singapore, 22-24 May 1997, pp. 196-201.

[29] **M.J. Gibbard, P. Pourbeik and D.J. Vowles**, "Coordination of multiple, distributed stabilizers in interconnected power systems", *invited paper for the CONTROL 97 Conference, Sydney*, 20-22 October 1997, pp. 458-463.

[30] **P. Pourbeik**, "Design and coordination of stabilizers for generators and FACTS devices in multimachine power systems", *Ph.D. Thesis, The University of Adelaide*, April 1997.

[31] **N. G. Hingorani**, "Power Electronics in Electric Utilities: Role of Power Electronics in Future Power Systems," *Proceedings of IEEE, Vol. 76, No. 4*, April 1988.

[32] **E. V. Larsen, J. J. Sanchez-Gasca and J. H. Chow**, "Concepts for Design of FACTS Controllers to Damp Power Swings", *IEEE Transactions on Power Systems, Vol. 10, No.2, pp. 948-956*, May 1995.

[33] **G. N. Taranto, J. H. Chow and H. A. Othman**, "Robust Decentralized Control Design for Damping Power System Oscillations," *Proceedings of the 33rd IEEE Conference on Decision and Control, pp. 4080-4085*, Orlando, FL, December 1994.

[34] **D. E. Goldberg**, "Genetic Algorithms in Search", *Optimization and Machine Learning*, Addison-Wesley, Reading, MA, 1989.

[35] **P. Ju, E. Handschin and F. Reyer**, "Genetic Algorithm Aided Controller Design with Application to SVC", *IEE Proceedings on Generation, Transmission and Distribution, Vol. 143, No. 3, pp. 258-262*, 1996.

[36] **V. Miranda, D. Srinivasan and L. M. Proença**, "Evolutionary Computation in Power Systems", *Proceedings of the 12th Power System Computation Conference*, Dresden, Germany, August 1996.

[37] **G. N. Taranto, J. K. Shiau, J. H. Chow and H. A. Othman**, "A Robust Decentralized Design for Multiple FACTS Damping Controllers", *IEE Proceedings on Generation, Transmission and Distribution, Vol. 144, No. 1, pp. 61-67*, January 1997.

[38] **G. N. Taranto and D. M. Falcão**, "Robust Decentralised Control Design Using Genetic Algorithms in Power System Damping Control", *IEE Proceedings on Generation, Transmission and Distribution, Vol. 145, No. 1, pp. 1-6*, January 1998.

[39] **A. L. B. do Bomfim, G. N. Taranto and D. M. Falcão**, "Simultaneous Tuning of Power System Damping Controllers Using Genetic Algorithms", *submitted to the IEEE Transactions on Power Systems*, in December 1997.

[40] **J.J. Sanchez-Gasca**, "Coordinated Control of Two FACTS Devices for Damping Interarea Oscillations", *IEEE Power Eng. Soc. Summer Meeting*, Berlin, Germany, July 1997. *IEEE paper: PE-802-PWRS-0-06-1997*.

[41] **S. Hirano, T. Michigami, A. Kurita, D.B. Klapper, N.W. Miller, J.J. Sanchez-Gasca, T.D. Younkins**, "Functional Design for a System Wide Multivariable Damping Controller", *IEEE Trans. Power System*, vol. 5, no. 4, Nov. 1990, pp. 1127-1136.

[42] **J.J. Sanchez-Gasca, N.W. Miller, A. Kurita, S. Horiuchi**, "Multivariable Control for Damping Interarea Oscillations in Power Systems", *IEEE Control Systems Magazine, vol. 9, no. 1*, Jan. 1989, pp. 28-32.

[43] **J. H. Chow, J.J. Sanchez-Gasca**, "Pole-Placement Designs of Power System Stabilizers", *IEEE Trans. Power System*, vol. 4, no. 1, Feb. 1989, pp. 272-277.

[44] **T. Hara, A. Kurita, T.D. Younkins, J.J. Sanchez-Gasca, J.H. Chow**, "A Coordinated Multivariable Control System Design for a HVDC Linked Remote ABWR Nuclear Power Park", *IEEE Trans. Energy Conversion*, vol. EC-2, no. 4, Dec. 1987, pp. 542-548.

[45] **T.D. Younkins, J.R. Winkelman, J.J. Sanchez-Gasca, J.A. McGrady**, "Output Feedback Multivariable Control for an Advanced Boiling Water Reactor", *IEEE Trans. on Energy Conversion*, vol. EC-2, no. 3, Sept. 1987, pp. 349-354.

[46] **Y. Tada, H. Ohkubo, A. Kurita**, "Multivariable Control Design for Damping Interarea Oscillations of Bulk Power Systems Using a Modal Reduction Technique", *IEEE Trans. on Power System*, Vol. 11, No. 1, Feb. 1996, pp. 295-302.

[47] **D. Arnautovic, J. Medanic**, "Design of Decentralized Multivariable Excitation Controller in Multimachine Power Systems by Projective Controls", *IEEE Trans. on Energy Conversion, Vol. EC-2, No. 4*, Dec. 1987, pp. 598-604.

[48] **W. E. Hopkins, Jr., J. Medanic, W. R. Perkins**, "Output Feedback Pole Placement in the Design of Suboptimal Linear Quadratic Regulators", *Int. Jou. Cont*., *Vol 34*, 1981, pp. 593-612.

[49] **C. D. Vournas, B. C. Papadias**, "Power System Stabilization via Parameter Optimization-Application to the Hellenic Interconnected System", *IEEE Trans. on Power Systems, Vol. PWRS-2, No. 3*, Aug. 1987, pp. 615-623.

[50] **C. D. Vournas, N. Maratos, B. C. Papadias**, "Power System Stabilizer Co-ordination Using a Parameter Optimization Method", *IEE Control 94 Conference*, Coventry, UK, March 1994.

[51] **N. Martins, H.P. Pinto and others**, "Retuning the Oscillation Damping Sources due to the North-South Brazilian Interconnection", *submitted to the SC38 CIGRE Paris Session*, August 1998.

[52] **V. A. Maslennikov and S. M. Ustinov**, "Method and Software for Coordinated Tuning of Power System Regulators", *IEEE Trans. on Power Systems*, Vol. 12, No. 4, Nov. 1997, pp. 1419-1424.

[53] **N. Martins and L. T. G. Lima**, "Eigenvalue and frequency domain analysis of small-signal electromechanical stability problems", in *IEEE Symposium on Applications of Eigenanalysis and Frequency Domain Methods*, 1989.

[54] **L.A.S. Pilotto, W.W. Ping and M. Szechtman**, "Converter Control Interactions on Multi-Infeed HVDC Systems", in *International Colloquium on HVDC and FACTS*, Montreal, September 1995.

[55] **M. Szechtman, L.A.S. Pilotto, W.W. Ping, E. Salgado, A.R.D. Carvalho, A. Wey, W.F. Long, F.L. Alvarado, C.L. DeMarco and S.L. Nilsson**, "The Behavior of Several HVDC Links Terminating in the Same Load Area", *Cigré Paper 14-201*, August, Paris, 1992.

[56] **L.A.S. Pilotto, W.W. Ping, A.R. Carvalho, S. Prado, A. Wey, W.F. Long, F.L. Alvarado, C.L. DeMarco and A. Edris**, "First Results on the Analysis of Control Interactions on FACTS Assisted Power Systems", presented at the *Flexible AC Transmission Systems (FACTS 3): The Future in High-Voltage Transmission*, Baltimore, October 1994.

[57] **T. Van Cutsem, C. D. Vournas**, "Voltage Stability Analysis in Transient and Mid-Term Time Scales", *IEEE Trans. on Power Systems, vol. PWRS-11*, February 1996, pp. 146-152.

[58] **CIGRE Task Force 38.02.11**, "Indices Predicting Voltage Collapse Including Dynamic Phenomena", *CIGRE*, July, 1994.

[59] **C. W. Taylor**, "Power System Voltage Stability", *McGraw-Hill*, 1992.

[60] **C. D. Vournas, N. D. Krassas**, "Voltage Stability as Affected by Static Load Characteristics", *IEE Proceedings, part C - Generation, Transmission and Distribution, Vol. 140, No. 3*, May 1993, pp. 221-228.

[61] **G. Andersson, P. Fischer de Toledo, G. Liss**, "HVDC Multi-Infeed Performance", *Proceedings of ICCEE'96*, August 1996, Beijing, China.

[62] **D.L.H. Aik and G. Andersson**, "Voltage Stability of Multi-Infeed HVDC Systems", *Transactions of IEEE on Power Delivery*, Vol. 12, No. 3, (1997) pp. 1309-1318.

[63] **S.S. Choi, R. Larkin, M.T. Bastik & A.W. Ferres**, "Effects of underexcitation limiters on operations of remote generating station", *IEE Proceedings, Part C, Vol. 138, No 6, pages 560-566*, November 1991.

## Appendix

### System Modeling

In this appendix the power system model is presented. The modeling must be flexible in the sense that detailed models of the power system equipments may easily be included. The control structure can be generic but the control structures currently used by the industry is privileged in this report.

### Power System

Assembling the models for each generator, load and FACTS device in the power system and connecting them adequately via the network algebraic equations, a set o differential-algebraic equations is obtained:

$$\dot{\mathbf{x}} = \mathbf{f(x,z,u)} \qquad (A.1)$$
$$\mathbf{0} = \mathbf{g(x,z,u)} \qquad (A.2)$$
$$\mathbf{y} = \mathbf{h(x,z)} \qquad (A.3)$$

where $\mathbf{x}$ is the state, $\mathbf{z}$ is a vector of algebraic variables, $\mathbf{u}$ is the input vector, $\mathbf{y}$ is the output vector and $\mathbf{f}$, $\mathbf{g}$, $\mathbf{h}$ are nonlinear functions.

The linearized system equations can be written as:

$$\dot{\mathbf{x}} = \mathbf{J}_1\mathbf{x} + \mathbf{J}_2\mathbf{z} + \mathbf{Bu} \qquad (A.4)$$
$$\mathbf{0} = \mathbf{J}_3\mathbf{x} + \mathbf{J}_4\mathbf{z} \qquad (A.5)$$
$$\mathbf{y} = \mathbf{C}_1\mathbf{x} + \mathbf{C}_2\mathbf{z} \qquad (A.6)$$

where $\mathbf{B}$ is the input matrix, $\mathbf{u}$ is the vector of input variables, $[\mathbf{C}_1,\mathbf{C}_2]$ is the output matrix. And $\mathbf{J}_1$, $\mathbf{J}_2$, $\mathbf{J}_3$ and $\mathbf{J}_4$ are submatrices of the non-reduced Jacobian matrix of the system.

The transfer function between an output $y_i$ and an input $u_i$ can be obtained from Eqs. (A.4)-(A.6) as [?]:

$$G(s) = \begin{bmatrix} \mathbf{c}_i^1 & \mathbf{c}_i^2 \end{bmatrix} \begin{bmatrix} s\mathbf{I} - \mathbf{J}_1 & -\mathbf{J}_2 \\ -\mathbf{J}_3 & -\mathbf{J}_4 \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{b}_i \\ \mathbf{0} \end{bmatrix} \qquad (A.7)$$

where $\mathbf{c}_i^1$ and $\mathbf{c}_i^2$ are the rows of $\mathbf{C}_1$ and $\mathbf{C}_2$ which correspond to the output $y_i$, and $\mathbf{b}_i$ is the column of $B$ which corresponds to the input $u_i$.

The state space model can be readily derived from Eqs.(A.4)-(A.6) by eliminating the algebraic variable leading to the following state space representation:

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} \qquad (A.8)$$
$$\mathbf{y} = \mathbf{Cx} \qquad (A.9)$$

## Controller Representation

The supplementary controller transfer functions (PSSs and FACTS supplementary controllers) are assumed as being of the form:

$$F(s) = \frac{K_c(1+sT_1)(1+sT_3)}{(1+sT_2)(1+sT_4)} \qquad (A.10)$$

where time constants $T_2$ and $T_4$ are assumed known and the remaining parameters $K_c$, $T_1$ and $T_3$ are determined by the setting procedure.

The controller can also be represented in the state space form as:

$$\dot{\mathbf{x}}_c = \mathbf{A}_c\mathbf{x}_c + \mathbf{B}_c y_i \qquad (A.11)$$
$$u = \mathbf{C}_c\mathbf{x}_c + \mathbf{D}_c y_i \qquad (A.12)$$

where $\mathbf{x}_c$ is the controller state vector, $y_i$ is the chosen stabilizing signal and $u_i$ is the controller output. Using Eqs. (A.8)-(A.9) to represent the power system and including the dynamical compensators given by Eqs. (A.11)-(A.12), the closed loop system can be represented by:

$$\begin{bmatrix} \dot{\mathbf{x}} \\ \dot{\mathbf{x}}_c \end{bmatrix} = \begin{bmatrix} \mathbf{A} + \mathbf{BD}_c\mathbf{C} & \mathbf{BC}_c \\ \mathbf{B}_c\mathbf{C} & \mathbf{A}_c \end{bmatrix} \begin{bmatrix} \mathbf{x} \\ \mathbf{x}_c \end{bmatrix} \qquad (A.13)$$