Status Report on Project Power System Stabilization

Hill, David J.

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LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

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David Hill

Department of Automatic Control
Lund Institute of Technology

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Department of Automatic Control
Lund Institute of Technology
P.O. Box 118
S-221 00 Lund Sweden

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Author(s)
David Hill

Supervisor
Karl Johan Åström

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by David J. Hill

Guest Researcher

Department of Automatic Control

Lund Institute of Technology, Sweden

Abstract

This report briefly summarises the work done during 1986, the first year of the power systems project at Lund. All effort was concentrated within the area of power system stabilisation. Descriptions of the background, ideas and anticipated publications are given irrespective of the current state of the work. The document is a snapshot of what was going on at the time of writing.

I.INTRODUCTION

After some exploring of the literature, work proceeded at two levels. Firstly, some fundamental studies on problems with a long-term view were identified. These were chosen with the needs of the interconnected Scandinavian (or Nordel) network in mind. The second aim was to develop some techniques which can be used to improve stability of this network in the short-term. Published motivation for work in this area is by Johansson et.al. (1982), Walve (1986).

The point of view taken in the project is to pursue application of theoretical techniques. The field of power systems engineering has not exploited the benefits of a mathematical understanding of the models used to the same extent as other fields in engineering. The early advances were made on the basis of raw intuition and simple calculation. With larger power networks and computers, more recently a dependence on numerical analysis techniques has grown. The solution of nonlinear algebraic equations (load flow), ordinary differential equations (simulation of responses) and optimisation problems (dispatch and scheduling) are standard tools. Questions on qualitative behaviour are typically addressed by repeated application of these methods. Some intuition is very often built up by looking at a single machine case only. This is inadequate in the study of modern power networks which are being forced to operate at higher power levels. To be specific, we aim to apply methods of stability theory and synthesis of stable control loops which have built up in the field of modern automatic control.

An example of a theoretically based technique which has been accepted widely is eigenvalue analysis for small disturbance stability. The result is that if all eigenvalues are in the left-half complex plane then the power network is small disturbance stable. Thus methods for stability enhancement can be based on pushing eigenvalues to good parts of the complex plane rather than running lots of simulations. (The latter is only needed to check things at the end.) Further theoretical results can help interpret unusual observations in numerical studies. An example is multiple solutions to load flows. It is now known that certain types of network can give more than one stable solution (to the nonlinear power flow equations). This is a very surprising fact which had been blamed previously on badly behaved algorithms.

The previous work in our chose direction has used rather diverse (and sometimes inadequate) models. A substantial part of the project became consideration of appropriate models on which analytical work can be done in a unified framework of stability analysis and security control.

The structure of the report is as follows. Section II describes the subprojects in a natural order (which does not represent the order of priority). Section III gives some conclusions and thoughts on the future of the project.

II.RESEARCH TOPICS

2.1 Unified View of Power System Stability and Security

Researcher: D.J.Hill

The author's previous power system research has been mainly in large disturbance stability. This began with results which suggested how deficiencies in the usual models for analytical studies could be overcome (Bergen and Hill, 1981). In the initial stages of the current project, there was cause to review the entire subject of power system stability. Within the confines of analytical issues, it was soon found that a point of view established in the earlier work could be used to make clear suggestions for useful further work. The scope of this was considerably beyond what was reasonable to consider in a one year project. Nevertheless, some overview of the ideas are presented here. This gives a context for the subjects worked on. It is also the basis of a novel course which is being designed and a monograph proposal for the new Springer- Verlag series on Electric Energy Systems and Engineering.

Power systems are very complex, but fortunately the models are cleanly defined and can be reasonably simplified with respect to time zones surrounding the instance of a disturbance. This enables essential phenomena to show up in models which are analytically tractable. However, we are dealing with coupled highly nonlinear differential-algebraic equations. A serious study of such systems requires many more mathematical tools than the approximate linearisation technique which so much power systems work is based on. A commentary of numerical and theoretical problems in differential-algebraic systems has been given recently by Mattsson (1986). The stability problem is traditionally split into small disturbance (or signal) stability (SDS) and large disturbance stability (LDS) problems. These can be answered using linearised and nonlinear models respectively. This terminology is preferred to the common terms of dynamic (in USA) and transient stability which are inconsistent with general stability terminology (IEEE, 1982). Also these concepts are understood as referring to synchronism behaviour in the literature.

Now the standard model for analytical studies (and often used in numerical ones) assumes impedance loads and then an equivalent impedance network coupling the generator internal voltages (Anderson and Fouad, 1977). This has the advantage of reducing the model to a set of nonlinear differential equations. It has the severe disadvantage of not allowing any questions to be addressed which deal with transmission network issues like tie-line limits, nonlinear loads and network voltages behaviour. It is totally generator oriented. We will argue that one consequence of this has been to limit the study of voltage stability largely to a steady-state phenomenon. A key part of the abovementioned earlier research is the use of models of the (simplified to ignore AVRs and governors) form

(1) $$\underline{M}_g \dot{\underline{\omega}}_g + \underline{D}_g \underline{\omega}_g + \underline{p}_g(\underline{\delta}, \underline{V}) = \underline{P}_g$$

(2a) $$\underline{p}_l(\underline{\delta}, \underline{V}) = \underline{P}_l$$

(2b) $$\underline{q}_g(\underline{\delta}, \underline{V}) = \underline{Q}_g$$

(2c) $$\underline{q}_l(\underline{\delta}, \underline{V}) = \underline{Q}_l$$

where $\underline{\delta}$ etc. denote vectors of load angles in the usual notation. Mathematically, the load constraints (2) define a manifold on which the generator state evolves. The subscripts refer to generator and load buses respectively. The steady-state version of these equations is just the normal load flow. The voltages $\underline{V}$ contains the generator internal and network voltages. The system structure has been preserved in this model; consequently, in the LDS context it was introduced with the term of structure preserving model. The aim there was to rigorously allow for nonlinear loads in the so-called energy function techniques. It is clear however that this is a good basis for studying stability problems associated with static VAR compensators and HVDC links. Also it leaves the option of studying voltage stability as a dynamic phenomena.

In fact a model such as (1)-(2) can be used to study the whole range of stability issues. At this point, we also introduce the issue of security as a major consideration. The standard terminology for operating states will be used (Elgerd, 1982). So we are not just concerned with stability analysis in the normal state. Most serious stability problems in practice come from contingencies occuring in the alert or emergency states. Methods are needed to analyse in these states, schedule operating points which have adequate security margin (preventive security control) and steer a system between states as occurs in emergency state control. Let us look briefly at a classification and status of topics in power system stability and security according to the above view.

A. Equilibria

The equilibria of (1)-(2) are just solutions of the usual load flow equations which are determined by the generation/loading schedule on the network. Typical practical situations demand consideration of one solution (obtained by initiating an algebraic equation solver at the so-called flat start). But these equations have numerous solutions most of which are small disturbance unstable. Stable and unstable solutions are denoted SEPs and UEPs respectively. The distribution of these is crucial to understanding LDS in any analytical way. Recently there has been studies of properties of these solutions using deeper mathematics for nonlinear equations. In particular Baillieul and Byrnes (1983) give a study based on algebraic geometry and differential topology which is limited to lossless PV bus networks. This falls considerably short of dealing with the general situation implied by (1)-(2), but is a substantial start to an important topic.

B. SDS Analysis

A striking example of the use of simple linear analytical methods is given in the classic paper of deMello and Concordia (1969). Observations of self-excited oscillations were explained using a model previously proposed by Heffron and Phillips for a single machine and AVR connected to an infinite bus via an external impedance. This is only third order and is defined by parameters denoted K_i. For Nordel readers, the model used by Lysfjord et.al. (1982) is just a transformed version of the Heffron-Phillips model with K_4=0 and and R_e=0.(The last assumption is dubious since it rules out local load.) It is of interest to extend the analysis to multimachine networks in order to expose instability mechanisms which reflect system structure. A multimachine version of the Heffron Phillips model has been given by Vournas and Fleming (1978), but again this is limited to impedance coupling. Some attention has been given in this project to revising this model to be structure preserving. This can then be subjected to analysis of conditions for negative damping and the effect of stabilisers. One outcome should be a generalisation of theoretical results by Wu and Liu (1986).

C. LDS Analysis

The main analytical work here is on energy function techniques which is covered in Section 2.4. Other work is on bringing geometric methods in to study more exotic behaviour. Salam et.al. (1984) have shown that the impedance coupling model can exhibit "chaotic motion" with zero damping.

An untouched area is analytical investigation of the effect of SDS stabilisers on LDS. Some practical observations indicate the importance of this problem (Anderson and Fouad, 1977), (Dineley and Mikhail, 1976).

D. Voltage Stability

This concept is associated with the observation that under certain operating conditions voltages can slowly reduce and finally collapse. An industry perspective on this problem has recently been given in by Falk Christensen et.al. (1986) where some explanations and guidelines for prevention are given. These are based on the usual single line static reasoning. Incidentally it uses the Swedish December 1983 contingency as a "good example of how a voltage collapse develops". The discussion mentions that this phenomenon could cause large disturbance instability in the obvious way, but seems to reject the idea that the reverse could also apply. The arguement is not convincing though because their model does not include the generator swing equation. The model (1)-(2) has the voltage as dependent variables in equations which include the static behaviour. Thus it should be a reliable forum to settle issues such as this. Also the above report indicates that voltage collapse is heavilly related to loading and transmission network structure- the precise strengths of our model. Most commentary on this problem is analytically naive. One interesting study is given by Liu and Wu (1985) where the dynamics of on-load tap changers is included in a linearised structure preserving model. Bounds on operating conditions are given to avoid small disturbance voltage instability.

E. SDS Enhancement

Our work on this topic is covered by Sections 2.2, 2.3. This aims to improve SDS by decentralised controllers.

Of course analytical results on acceptable operating conditions can help devise principles to keep secure operation in this form of stability (Sastry and Varaiya, 1980). However, these have not yet given a procedure which would be considered by industry.

F. LDS Enhancement

A strong potential use of energy function methods is in devising schemes for security control. Besides fast stability assessment, a measure of stability margin in terms of operating conditions and parameters is given. For instance rescheduling to improve this margin becomes a way of increasing security. An ad hoc implementation of this idea in the Tokyo power system was reported by Saito et.al. (1985). An analytically based technique was given by Chandrashekhar and Hill (1983) using a simple structure preserving model and Narasimhamurthi (1984) using the impedance coupled model. Using our recent improvements to modelling these results can be improved.

The subject of emergency state control has been made prominent in the control field by Zaborszky. One of the recent papers which includes HVDC links is (Zaborszky et.al., 1984). These results aim to give large disturbance stabilisers which require only local information provided control means such as damping resistors or load shedding are available. This work again uses impedance coupled models which only allows the links with poor treatment of loads. Our model would straighten this out and also allow means like switched capacitor banks and give the whole scheme in terms of actual (not reduced) network quantities.

A recent tend in more practical stabiliser development has been to include nonlinear controls to give a coordinated improvement of SDS and LDS (Musaazi et.al., 1986), (Lee and Kundur, 1986), (Ishiguro et.al., 1986). The possibilities here for coordinated tuning are obvious but somewhat intimidating for analytical treatment at this stage.

G. Voltage Stability Enhancement

This topic is receiving more attention following incidences of voltage collapse in Western Europe (besides the Swedish one). A technique that has emerged is secondary voltage-VAR control whereby operators modify the input reference on AVRs to achieve a satisfactory voltage profile in the face of large disturbances. Thorp et.al. (1986) give an optimal solution for the control strategy based on linearised Q-V equations (i.e. eqns.1c,d). The fact that this control action can be used to improve LDS reinforces the abovementioned inclination to treat the two concepts within the same model. Perhaps we can hope for an automatic large disturbance stabiliser for synchronism and voltage.

We anticipate that the field of expert systems will play a role in future implementation of these more sophisticated control schemes. Wehenkel et.al. (1986) reports an investigation in this direction for energy function methods.

2.2 Coordinated Tuning of Power System Stabilisers(PSS)

Researchers: B.Eliasson, D.J.Hill.

The aim is to consider ways to coordinate the tuning of all sources of damping in the network including generator PSS, HVDC links and SVCs. Further this tuning should be robust to changes in operating conditions Currently,the Nordel stabilisers are tuned according to local responses if at all. Thus they can be at most useful on local modes. If broadband tuning is possible, system modes get positive but an unreliable level of damping. We claim that a secure tuning to damp system modes is virtually impossible without coordination. The work is more ambitious than previous attempts in other countries by including all sources of damping and the effect of nonlinear loads. This has required some considerable attention to modelling using a linearised form of eqns. (1)-(2) as a starting point.

This project is in two parts consisting of the study of sensitivity of system modes to stabiliser parameters and the development of an algorithm for coordinated tuning of these parameters. We start with the sensitivity study. This follows the spirit established by deMello et.al.(1980) of using simplified models, but their work did not make use of sophisticated formulas for eigenvalue sensitivity (and used generator network models). We have developed a (simplified) model of the form

(3) $$\underline{M}\,\underline{\omega} + \underline{D}\,\underline{\omega} + \underline{K}_1\underline{\delta} = \underline{0}$$

where

(4a) $$\underline{M} = \underline{M}_g + \underline{K}_2\underline{G}_2$$

(4b) $$\underline{D} = \underline{D}_g + \underline{T}\,\underline{G}_3\underline{T}^t + \underline{K}_2\underline{G}_1$$

The diagonal matrices $\underline{G}$ contain the gains in the PSS (K_{se} and K_{sed} in ASEA version) and HVDC link stabilisers. The addition of SVCs and PSS based on network quantities should be straightforward. Using model (3)-(4) and some matrix theory tools, the main product is a sensitivity matrix showing the sensitivity of damping on each mode to all stabiliser parameters. This can be presented for different loading conditions. It shows immediately which damping sources have no effect and which are crucial for any given mode. (Modes with no parameter effecting them are related to the concept of fixed modes in system theory.) Obviously, the crucial ones should be emphasised in tuning. The techniques are applied to a reduced order model of the Nordel network. This has been developed within Southern Sweden Power Supply (Sydkraft) by B.Eliasson and S.Lindahl and the latest version consists of 16 coherant groups. A report on this work is in preparation. As a theoretical sideline to this activity, some generalisations of recent results on small disturbance stability by Wu and Liu (1986) have been studied.

There has been quite a lot of previous research on coordinated tuning. This can be classified into sequential or simultaneous tuning methods. Sequential methods are provided by Fleming et.al. (1981) and Abdalla et.al. (1984). These attend to each stabiliser in turn on the basis of sensitivity and can allow for the network interactions. But there is an obvious problem of eigenvalue drift which requires iteration. The general style of simultaneous tuning is to use optimisation to find parameter settings which ensure the closed loop eigenvalues are close to desired locations. The problem is sometimes posed as one of decentralised pole assignment (where for tuning we assume a given controller structure). Lim and Elangovan (1985) have given a very simple technique for solving this problem, but like other work (Lefebvre, 1983) this goes too far in giving exact pole placement. We have preferred to aim at just ensuring the eigenvalues are in acceptable regions. This leaves flexibility to achieve other things. The choice of the eigenvalue regions is of course not a minor matter. For instance, one relevant issue which gets ignored in the literature is the compromise needed to ensure the voltage mode is not excited (see Section 2.3). Pai et.al (1980) and Sivakumar et.al. (1984/85) have used this approach to tuning in more limited situations. We are investigating many formulations and further testing is being done in a Master's thesis. Of particular concern is to ensure that the tuning is robust with respect to variable operating conditions. This is virtually ignored in the literature; however, a lot of oscillation problems in practice arise after some removal of equipment or contingency. Of course, the final tuning is done with a more complete model than (3)-(4). A further problem which has not been addressed in the literature is how to tune large numbers of stabilisers. We have devised a scheme for this which makes use of the fact that the most troublesome system modes are presented within reduced coherent groups models. This structures the problem considerably. These modes are sensitive to stabilisers in certain areas. This scheme remains to be tested.

2.3 New Generator PSS Synthesis

Researchers: D.J.Hill, B.Wittenmark and M.Akke

In this section the aim is to look at techniques for deriving new controller structures. This subject begs attention. The pioneering paper of deMello and Concordia (1969) revealed that the voltage control loop can inject negative damping into the rotor oscillations of a single machine connected to an infinite bus. This could be fixed by feedback from the angular frequency to the voltage summing junction. A lot of work followed which studied different signals to drive the stabiliser (Larsen and Swann, 1981). A large number of stabilisers in the Nordel network are the ASEA type based on electrical power as an approximation to accelerating power (change). This has the problem that it must be disabled for sudden changes in mechanical power. Substantial advances were made by deMello et.al. (1978, 1982) where an "observer" for accelerating power is devised and used in a digital controller. However all this seems limited by the basic structure. It is derived from single machine reasoning as a modification to an unsophisticated AVR design. (which inter alia ignores the interaction with inertial part). This has several disadvantages:

1.There is no accounting in the structure for the machines participation in system modes. Surely, this is why tuning for that situation is difficult.

2.The problem is attacked somewhat indirectly. Starting from first principles it is clear that the AVR-PSS should be designed in a coordinated fashion. Rather than patch up the AVR , design it including specifications on damping of the inertial loop.

The control ideas brought to bear on the problem in the above work are elementary classical. The full range of modern control ideas should be considered. Computer control enables us to use more complicated controllers than those designed with analog implementation in mind. DeMello et.al. (1982) have not exploited this possibility. The problem of tuning for variable operating conditions suggests consideration of adaptive or nonlinear control.

We started this project with visions of applying state variable feedback/ observer, linear quadratic, polynomial and coprime factorisation methods to synthesise an AVR which robustly (with respect to variable operating point) tracks a voltage reference while rejecting disturbances, and damping a local and system mode. Actually some work in the modern vein has been done. The most popular approach has been LQ methods. We do not favour these here because of the aim to guarantee a level of damping. Mohan et.al. (1978) provided an alternative state feedback excitation controller based on pole placement for single machines. A brief study of observer design is by Lim and Choi (1980). Another (somewhat dubious) option provided by Padiyar et.al. (1980) is to approximate the state law by one based on output variables. These authors and Soliman and Fleming (1983) also give a procedure to derive dynamic output feedback controllers (in multimachine case) for pole placement. These methods are closely related to the tuning procedure given by Lefebvre (1983). Abe and Doi (1983) give a pole assignment technique based on simple transfer function methods which allows for multimachine coupling and nonlinear loads. This is a bit more in the spirit we are after. Groups at the University of Calgary and Electricité de France have been working on adaptive control of voltage for some time. The papers by Kanniah et.al.(1983) and Irving (1980) are representative of this work. They take the self-tuning regulator approach developed at Lund (Åström and Wittenmark, 1973) and model-reference approach respectively.

All this work using modern control methods has not come up with a universal controller structure to compete with those following deMello and Concordia (1968). This is a more realistic aim. So we will endeavour in this project long-term to produce a parameter tunable structure which in principle could be translated to a commercial unit. Although the design may be based on exact pole placement, the tuning would be according to principles given in Section 2.2. The point is that the structure will have more freedom to accomodate system modes.

The control department at Lund has a number of useful software tools for modern synthesis techniques. As a starting point for work in this area a state-space version of the Heffron-Phillips model with computation of the K_i parameters from external conditions (Anderson and Fouad, 1977) for a single machine on an infinite bus was implemented in CTRL-C.(This is the model made famous by deMello.) A state variable feedback synthesis was developed including reset action and anti-reset windup facility. This was tested using data from Harsprånget power station in North Sweden. Robustness of the design can be simply studied by varying the external conditions. Allowing for saturation nonlinearities in the system cannot be done in CTRL-C for response testing. Thus SIMNON became a useful tool. This simulation program has been developed at Lund. A report on this work is nearly complete. The project took lower priority than the one on coordinated tuning, but is an ideal one for this department to follow up on. Software facilities for polynomial design which have recently become available should be useful.

It is well-known that the inertial and voltage modes can be badly damped and are influenced by the stabiliser (Anderson and Fouad, 1977). Our coordinated design approach has clarified a fundamental compromise here. It is worthwhile to elaborate. A transfer function model of the generator plus exciter takes the form

$$(5)\qquad \begin{bmatrix} \delta(s) \\ V_t(s) \end{bmatrix} = \frac{1}{P(s)} \begin{bmatrix} K_{11}(s + \beta_{11}) & -K_{12} \\ K_{21}(s + \beta_{21}) & K_{22}\,(s^2 + 2\zeta_1\omega_1 s + \omega_1^2) \end{bmatrix} \begin{bmatrix} T_m(s) \\ \vartheta_e(s) \end{bmatrix}$$

where

$$P(s) = (s + \alpha_1)(s + \alpha_2)(s^2 + 2\zeta_o\omega_o s \; + \omega_o \;)$$

The inputs are mechanical torque and exciter voltage. The outputs are rotor angle and terminal voltage (magnitude). P(s) contains open-loop exciter, field and inertial modes. The voltage loop transfer function dependence on the inertial effects is now clear. The zeros are very close to the poles. Shifting these poles to improve damping on δ will expose this mode in the voltage. This becomes an interesting synthesis exercise. Actually, to incorporate the effect of system modes, we should study a simple system which captures that behaviour. This suggests looking at a two generator system where each generator represents the areas swinging against each other. DeMello and Laskowski (1975) effectively recognise the need for this extension. A multimachine Heffron-Phillips model would be useful here. The version given by Vournas and Fleming (1978) is limited by assumption of impedance coupling and so, like its predecessor, cannot account for nonlinear loads.

A very promising idea suggested by Bollinger et.al. (1979) is to include tie-line power in the signals available to a generator PSS. With the approach of studying structure preserving models it becomes natural to follow this up.

We did not get to the point of considering adaptive or nonlinear control seriously for new PSS. The robustness properties observed in the pole assignment design compelled us to first address the question of whether a fixed gain controller is adequate. Some basic ideas on this issue in control are being developed at Lund (Åström et.al., 1986).

2.4 Energy Function Methods (EFMs) for Large Disturbance Stability

Researcher: D.J.Hill

As mentioned above this was the main subject of previous power systems research by the author. A recent summary of basic concepts of EFMs and recent research is given by Hill and Hiskens (1985). This also describes the beginnings of a project with the Queensland Electricity Commission on using these methods to assist operation of the power network. The subject has a long history which can be studied in various surveys including those of Pai (1981) and Ribbens-Pavella and Evans (1985). The most active promotion of EFMs is led by Fouad at Iowa State University. Recently, they have teamed up with Ontario Hydro in projects for EPRI, USA. Several papers are coming through the IEEE PWRS Transactions on this work.

The standard model for EFMs work has been the impedance coupled generators one. The paper (Bergen and Hill, 1981) started a line of work on using models of the type (1)-(2). Initially, this was done to overcome certain analytical difficulties. However, the main virtues of this line are that nonlinear loads and transmission network structure can be accounted for in the stability assessment. We believe this model is a better basis for many practical problems.

Early in 1986, an improved stability analysis of the model (1)-(2) was carried out. This is reported in (Hill and Chong, 1986). Later in the year strong interest was expressed in EFMs by the Sydkraft group and researchers in the Swedish Institute of Applied Mathematics (ITM) who are doing a pilot study for ASEA in this area. From these discussions, two aspects of our approach seem particularly pertinent to the Nordel system:

A.Concept of Vulnerable Cutsets

From the early paper (Hill and Bergen, 1981), we have formulated stability assessment in terms of so-called vulnerability indices which give network strength in terms of conditions on cutsets of the transmission network. This idea has emerged recently (and more vaguely) in an industry study (Lotfalian et.al., 1986). We believe that this concept can be exploited much further. It was the basis of a preliminary dynamic dispatch technique (Chandrashekhar and Hill, 1983).

B.Allows HVDC, SVC

Pai (1981) suggested that our structure preserving models were very promising for analysis of networks with HVDC links. These cannot be cleanly included in the usual models because all the transmission network buses are eliminated. This aspect has not been pursued until this year. (There are no HVDC links in Australia.) The addition of HVDC links and SVCs to model (1)-(2) is straightforward and studies have begun.

III.CONCLUSIONS

This report has summarised the range of activities begun in the power systems project. Included in this has been an overview of large parts of analytical methods in power systems stability and security. This is seen to be a field where a lot of fundamental research remains. Most of it seems to address problems of current concern in the Swedish power industry.

At this stage, three other reports are in preparation, a course/monograph initiated and Lund students have one Ph.D, one Licentiate and one Masters projects to finish. These documents will give a complete reporting of the work.

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References

Abdalla,O.H., S.A.Hassan and N.T.Tweig (1984). Coordinated stabilization of a multimachine power system. IEEE Trans. PAS, 103, 483-494.

Abe,S. and A.Doi (1983). A new power system stabilizer synthesis in multimachine power systems. IEEE Trans. PAS, 102, 3910-3918.

Anderson,P.M. and A.A.Fouad (1977).Power System Control and Stability Iowa State University Press, Ames, Iowa.

Åström,K.J. and B.Wittenmark (1973). On self-tuning regulators. Automatica, 9, 185-199.

Åström,K.J., L.Neumann and P.O.Gutman (1986). A comparison between robust and adaptive control of uncertain systems. Proc. 2nd IFAC Workshop on Adaptive systems in Control and Signal Processing, Lund, Sweden, 37-42.

Baillieul,J. and C.I.Byrnes (1983). The load flow equations for a 3-node electrical power system. Systems and Control Letters, 2, 321-329.

Bergen,A.R. and D.J.Hill (1981). A structure preserving model for power system stability analysis. IEEE Trans. PAS, 100, 25-35.

Bollinger,K.E., R.Winsor and A.Campbell (1979). Frequency response methods for tuning stabilizers to damp out tie-line power oscillations: theory and field-test results. IEEE Trans. PAS, 98, 1579-1515.

Chandrashekhar,K.S. and D.J.Hill (1983). Dynamic security dispatch: basic formulation. IEEE Trans. PAS, 102, 2145-2154.

deMello,F.P. and C.Concordia (1969). Concepts of synchronous machine stability as affected by excitation control. IEEE Trans. PAS, 88, 316-329.

deMello,F.P. and T.F.Laskowski (1975). Concepts of power system dynamic stability. IEEE Trans. PAS, 94, 827-833.

deMello,F.P., L.N.Hannett and J.M.Undrill (1978). Practical approaches to supplementary stabilizing from accelerating power. IEEE Trans. PAS, 97, 1515-1522.

deMello,F.P., P.J.Nolan, T.F.Laskowski, and J.M.Undrill (1980). Coordinated application of stabilisers in multimachine power systems. IEEE Trans. PAS, 99, 892-901.

deMello,F.P., L.N.Hannett, D.W.Parkinson and J.S.Czuba (1982). A power system stabilizer design using digital control. IEEE Trans. PAS, 101, 2860-2868.

Dineley,J.I. and S.E.Mikhail (1976). Effect of feedback stabilising signals in excitation and governors/turbine systems on transient and dynamic stability. Paper A 76 113-1, IEEE PES Winter Power Meeting, New York.

Elgerd,O.I. (1982). Electric Energy Systems Theory, Macgraw-Hill, New York.

Falk Christensen,J. et.al. (1986). Planning against voltage collapse. CIGRE SC 38-01 TF03 Report.

Fleming,R.J., M.A.Mohan and K.Parvatism (1981). Selection of parameters of stabilizers in multimachine power systems. IEEE Trans. PAS, 100, 2329-2333.

Hill,D.J. and C.N.Chong (1986). Energy functions for power systems based on structure preserving models. Proc. 25th IEEE Conf. on Decision and Control, Athens, Greece.

Hill, D.J. and I.A.Hiskens (1985). Prospects for rapid large disturbance stability assessment. Proc. Electric Energy Conference, Newcastle.

IEEE Committee Report (1982). Proposed terms and definitions for power system stability. IEEE Trans. PAS, 101, 1894-1898.

Irving,E. (1980). New developments in improving power network stability with adaptive generator control. In K.S.Narendra and R.V.Monopoli (Eds.), Applications of Adaptive Control, Academic Press, New York, 221-244.

Ishiguro,F., et.al. (1986). Coordinated stabilizing control of exciter, turbine and braking resistor. IEEE Trans. PWRS, 1, 74-80.

Johansson,T. et.al. (1982). Stability problems in the Nordic power system. Paper

36-06, CIGRE Meeting, Paris.

Kanniah,J., O.P.Malik and G.S.Hope (1983). Excitation control of synchronous generators using adaptive regulators-PartsI,II. IEEE Trans. PAS, 102, 220-327.

Larsen,E.V. and D.A.Swann (1981). Applying power system stabilizers Parts I, II,III. IEEE Trans. PAS, 100, 3017-3046.

Lee,D.C. and P.Kundur (1986). Advanced excitation controls for power system stability enhancement. Paper 38-01, CIGRE Meeting, Paris.

Lefebvre,S. (1983). Tuning of stabilizers in multimachine power systems. IEEE Trans. PAS, 102, 290-299.

Lim,C.-M. and Choi,S.S. (1980). Control of power systems using minimal- order observers. Comput. and Elect.Engng., 7, 211-215.

Lim,C.-M. and S.Elangovan (1985). A new stabiliser design technique for multimachine power systems. IEEE Trans. PAS, 104, 2393-2400.

Liu,C-C. and F.F.Wu (1985). Steady-state voltage stability regions of power systems. Systems and Control Letters, 6, 23-31.

Lofthalian,M. et.al. (1986). A stability assessment methodology. IEEE Trans. PWRS, 1, 84-91.

Lysfjord,T. et.al. (1982). Förbättrad dämpning av effektpendlingar i nordelnätet genom optimering av inställbara reglerparametrar för dämptillsatser. NORDEL Dynamiska Gruppen Rapport 1982-06-15.

Mattsson,S.E. (1986). On differential/algebraic systems. Report TFRT-7327, Department of Automatic Control, Lund Institute of Technology, Sweden.

Mohan,M.A., K.Parvatisam and S.V.M.Bhuvanaika Rao (1978). Design of supplementary stabilizing signals for synchronous machines by state feedback and eigenvalue placement. Paper A 78 249-5, IEEE PES Winter Meeting, New York.

Musaazi,M.K., R.B.I.Johnson and B.J.Cory (1986). Multimachine system transient stability improvement using transient power system stabilizers (TPSS). Paper 86

WM 201-8, IEEE PES Winter Meeting, New York.

Narasimhamurthi,N. (1984). On-line real power sheduling in marginally secure power systems. IEEE Trans. PAS, 103, 869-873.

Padiyar,K.R., S.S.Prabhu, M.A.Pai and K.Gomahti (1980). Design of stabilizers by pole assignment with output feedback. Int.J.Electrical Power and Energy Systems, 2, 140-146.

Pai,M.A., K.R.Padiyar and P.S.Shetty (1980). Sensitivity based selection of control parameters for multi-machine power systems. Paper A 80 020-8, IEEE PES Winter Meeting, New York.

Pai,M.A. (1981). Power System Stability, North-Holland Pub. Co., New York.

Ribbens-Pavella,M. and F.J.Evans (1985). Direct methods for studying dynamics of large-scale electric power systems- a survey. Automatica, 21, 1-21.

Saito et.al. (1975). Security monitoring systems including fast transient stability studies. IEEE Trans. PAS, 94, 1789-1805.

Salam,F.M.A., J.E.Marsden and P.P.Varaiya (1984). Arnold diffusion in the swing equations of a power system. IEEE Trans. Circuits and Systems, 8, 673-688.

Sastry,S. and P.Varaiya (1980). Hierarchical stability and alert state steering control of interconnected power systems. IEEE Trans. Circuits and Systems, 27, 1102-1112.

Sivakumar,S., A.M.Sharaf and H.G.Hamed (1984/85), Electric Power Systems Research, 8, 275-284.

Soliman,H.M. and R.J.Fleming (1983). Minimal-order decentralised stabilizers for interconnected power systems. Int.J. Systems Sci., 14, 765-776.

Thorp,J.S., M.Ilic-Spong and M.Varghese (1986). An optimal secondary voltage-VAR control technique. Automatica, 22, 217-221.

Vournas,C.D. and R.J.Fleming (1978). Generalization of the Heffron-Phillips model of a synchronous generator. Paper A 78 534-0, IEEE PES Summer Meeting, Los

Angeles.

Walve,K. (1986). Modelling of power system components at severe disturbances. CIGRE Report to appear.

Wehenkel,L., T.V.Cutsem and M.Ribbens-Pavella (1986). Artificial intelligence applied to on-line transient stability assessment of electric power systems. Proc. 25th IEEE Conf. on Decision and Control, Athens, Greece.

Wu,F.F. and C-C.Liu (1986). Characterization of power system small disturbance stability with models incorporating voltage variation. IEEE Trans. Circuits and Systems, 33, 406-417.

Zaborszky,J., G.Huang and L.J.Chiang (1984). On line stabilization of the large HV-AC-DC power system by using observation decoupled reference as a system-wide target. IEEE Trans. PAS, 103, 788-797.