The University of Manitoba

MODELLING OF INTEGRATED MULTI-AREA MULTI-TERMINAL DC-AC SYSTEMS AND THE DESIGN OF STABILIZING LOOPS IN DC CONTROLS

By

ADEL MAHMOUD M. SHARAF

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Filfilment of the Requirements for the Degree
of Doctor of Philosophy

DEPARTMENT OF ELECTRICAL ENGINEERING

WINNIPEG, MANITOBA R3T 2N2
CANADA

May, 1979

MODELLING OF INTEGRATED MULTI-AREA MULTI-TERMINAL DC-AC SYSTEMS AND THE DESIGN OF STABILIZING LOOPS IN DC CONTROLS

BY

ADEL MAHMOUD MOHAMED SHARAF

A dissertation submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements of the degree of

DOCTOR OF PHILOSOPHY

To

My parents, my wife Sawsan
and my son Mahmoud.

ABSTRACT

Multi-terminal HVDC systems overlayed on multi-area power pools are expected to emerge in the near future to provide a superior stabilizing influence under large scale and small disturbances in addition to providing necessary ties between areas. The thesis shows the analysis and procedure required for designing the most effective stabilizers for dc converter controls. First, a linearized small displacement model is derived for a simulated ac-dc system. This model is later used to show the effectiveness of various feed backs in stabilizer loops. The second part of the work investigates the effectiveness of different damping signals and transfer functions in stabilizing loops based on frequency modulation of dc power or current orders. It is found that the stabilizer gain-sensitivity to dc power level is minimal. Optimal fixed-gain stabilizers are designed. Considering the complexity and reliability of having all the states available at each dc terminal station suboptimal stabilizers based on frequency deviation are designed. It is shown that by modulating the power order by frequency and angle slip variation a very effective damping control for the multi-area ac system is achieved. A number of results are obtained for a sample system. Comparision of the system response due to small disturbances shows clearly a remarkable damping provided by the stabilizers derived from the linearized model.

The effectiveness of such stabilizers in damping small scale disturbances is also investigated.

The research is divided into three major areas:

1) Derivation of mathematical models to represent integrated ac-dc system of complex configuration.

2) Design of stabilizing loops in dc controls.

3) Parametric study of the effect of system parameters on dynamic stability.

The study develops a generalized analytic method for system linearization which should be readily accessible for developing state variable representations as well as a reference system for development of generalized linearization techniques.

The work is dedicated to this class of stability problem due to small scale disturbances which is defined as dynamic stability. It is to be noted that linearization of system equations restricts the applicability of system linearized mathematical models to only the assessment of dynamic stability. Transient stability due to large scale disturbances such as faults requires simulation of non-linear systems in great detail and is out of the scope of the study presented herein.

ACKNOWLEDGEMENTS

The author expresses deep gratitude to Professors R.M. Mathur, R.W. Menzies, D.W. Trim, Dean L.M. Wedephol, and Mr. K.R. Ouelette for serving on his Advisory Committee.

The author wishes to express his sincerest thanks and appreciation to Professor R.M. Mathur for his support and guidance in the preparation of this thesis.

A special thanks to Messrs. A.P. Barsalou and M. Musick of Manitoba Hydro for their understanding and encouragement. Thanks are also due to The University of Manitoba for financial support and Manitoba Hydro for co-operation during the course of this research.

I would like to express my appreciation to Mrs. P. Giardino for her untiring effort in typing the manuscript.

Finally, the author expresses sincere appreciation to his parents and his wife for their patience, support, encouragement and love.

TABLE OF CONTENTS

Page

APPENDICES

LIST OF FIGURES

LIST OF TABLES

LIST OF MOST USED SYMBOLS

Δ	Incremental operator.
a_1, a_2, a_3	Equivalent constants due to load at buses.
A	State matrix.
A_1, A_2, A_Z, A_{ZZ}	Coefficient matrices.
B	Control matrix.
$\underline{P}$	Riccati matrix.
H, H_m, T_m	Transformation matrices in dc transmission solution.
E_i	Internal emf.
G_{Li}, B_{Li}	Load conductance and susceptance.
P_{dri} I_{dri}	Power and current settings at terminal i.
I_{dci}	DC current at terminal i.
Q, R	Weighting state and control matrices respectively.
J	Performance criterion
I_{i2} I_{i3}	AC current at inverter terminals 2 and 3.
I_{r1}	AC current at rectifier terminal 1.
K_{Li}, T_i	Gain and time constant of α-control at terminal i.
M_i	Inertia coefficient of area i.
P_{di}	DC power at terminal i.
P_i	Electrical power at area i.
P_{Mi}	Mechanical power of area i.
P_t, P_{t1}, P_{t2}	AC tie line powers.
V_{dci}	DC voltage at terminal i.
V_i	AC bus voltage.
x_i	Transient reactance of area i.

x_{ii}	Inverter commutation reactance of terminal i.
x_{ri}	Rectifier commutation reactance of terminal i.
$R_{di}=R_{dci}+\frac{3xri}{\pi}$	Equivalent dc link resistance.
L_{Ti}, L_{Si}	DC transmission and smoothing reactor inductances respectively.
x_t, x_{t1}, x_{t2}	Tie line reactances.
P^*_{dri}, I^*_{dri}	Modified dc power and current settings at terminal i.
ϕ_{ri}	Power Factor angle at dc terminal i.
α_i	Control angle at terminal i.
δ_i	Extinction angle at terminal i.
θ_i	Rotor angle of area i.
ϕ_i	AC bus angle of area i.
$\phi_1', \phi_2', \phi_3'$	Resultant ac bus angles with load.
ω_i	Angular speed of area i.
$1:N_i$	Converter transformer turns ratio at terminal i.
B_i	Number of dc bridges in series at terminal i.
$K_i = \frac{3\sqrt{2}}{\pi} N_i B_i$	AC-DC transformation constant at terminal i.
$\cdot$	Denotes differentiation of the vector.
$p = \frac{d}{dt}$	Heaviside operator.
V_{dr}	Preset dc voltage at terminal i.
C.C.C.	Constant current control.
C.E.A.	Constant extinction angle control.
C.V.C.	Constant voltage control.
S.C.R.	Short Circuit Ratio.
$\underline{x}$	State vector.
$\underline{u}$	Control vector.
$\hat{}$	Denotes transformation.

T	Denotes transpose of an array.
T_{pi}	Stabilizer time constant at terminal i.
$[H]$	Hamiltonian matrix.
λ_j	Eigen value (j) of integrated ac-dc system.
$[V]$	Eigen vector matrix of integrated ac-dc system.
K_{Li}, T_i	Current controller gain and time constant at terminal i.
$(\Delta\delta_i)$	Incremental variation in power angle of area i.
$\Delta\theta_{ij} = \frac{\Delta\omega_{ij}}{p}$	Angle slip deviation between areas (i) and (j).
ΔP_{ac}, ΔI_{ac}	Incremental variations in ac tie line power and current respectively.
$K_{\theta ij}$, $K_{\omega i}$	Stabilizer gains.
$[T_s],[T_1],[T_a]$ $[T_r],[T_p]$	Transformation matrices utilized in system models.
ms	Millisecond
R, I	Denotes Rectifier and Inverter operation respectively.
AVR	Automatic voltage regulator.
$\Delta\psi_{fdi}$, $\Delta\psi_{Kdi}$, $\Delta\psi_{Kqi}$	Incremental variations in field and amortisseur direct and quadrature flux linkages at machine i respectively.
ΔE_{ti}	Incremental variation in machine i terminal voltage.
ΔT_{mi}	Incremental variation in mechanical power at machine i.
$\Delta\alpha_i$	Incremental variation in control angle at dc terminal i.
D_i	Damping coefficient at area i.
$Y_{ij} \angle \psi_{ij}$	Transfer admittance between nodes (i) and (j).

CHAPTER 1

INTRODUCTION

1.1 Introduction and Background

Would your province, state or power utility have an HVDC link by 1990? The chances are that if they do not have one by then, they may be thinking about one. The application of HVDC power transmission has come a long way since early sixties. Indeed the EPRI Projections[1] are that in the next seven to eight years, the global usage of HVDC will triple.

HVDC transmission is used for a variety of reasons. Some well known are: bulk power transmission over long distances, asynchronous ties joining either dissimilar frequency areas or large power pools by a small capacity link, use of dc cables for crossing a water body or feeding heavy density areas and for incorporating an efficient, fast, active-power controller to enhance the stability of interconnected areas. Usually, HVDC transmission is chosen for a combination of the above reasons.

The author believes that while most of the existing HVDC transmission systems may not have been chosen for stabilization role, their fast controllability is such an attractive feature that it is well recognized as an important asset for the systems. In future this may play a decisive role in the selection of HVDC transmission systems especially for interconnections between complex multi-area systems.

HVDC network is expected to grow from point-to-point schemes to multi-terminal[2-5] schemes. A number of feasibility studies of multi-terminal systems overlayed on multi-area interconnected ac systems have already been performed. Since Manitoba Hydro has the largest operating HVDC system of the world and may be a pioneer in the application of multi-terminal systems, our interest in this activity is understandable. From the hardware and reliability point of view the climate is inducive to the realization of multi-terminal systems.

The thesis deals with the stabilization role of multi-terminal HVDC systems by frequency modulation of current or power order. The active power control for stabilization is a well known concept and is accomplished by governor controls in pure ac systems. The potentiality of HVDC links in this role was proposed in 1964 by Dr. Uhlmann[6]. A number of theortical studies [6-12,16] and results of some practical implementations[15] have subsequently appeared.

Uhlmann[6] investigated the use of dc link controls to stabilize an ac transmission system through the use of frequency deviations as the control parameter. His work was based on a simplified ac system model, by assuming zero ac system impedance, zero time delay for the dc controls and unity power factor at converter stations.

Machida[7] indicated that the dc controls through the rapid change in dc power settings could be used effectively to improve system transient stability, subsequent to large scale disturbances.

Krause, et al[8-9] made an analog and hybrid simulation of interconnected ac-dc systems and studied the effectiveness of different control strategies for different types of faults.

Goudie[10] investigated the steady state stability regions by using a linearized mathematical model for inter-connected ac-dc systems.

A recent paper by Dash[11], et al showed that the feed-back gains derived from the application of optimal control theory on the linearized state equations of the composite system can be used in a non-linear power system under large scale disturbances. This was found quite effective in improving both the transient as well as dynamic stability.

Klein[12], et al, developed a hybrid model simulator of a parallel ac-dc system and investigated the effectiveness of different ac and dc control arrangements on the dynamic stability of the integrated system. Effectiveness of ac and dc control interaction on the natural and generated modes of oscillations were well demonstrated in their paper.

Kobayashi[13] investigated a switching type controller, where the dc control settings are timely switched according to Pontryagin's Maximum Principle[14]. It was shown that this would improve the transient stability. The feed back state variables used were the phase angle and angular velocity.

Most of the work referred to above reveals the possibility of using ac intertie power, frequency and/or angle deviations to improve the dynamic as well as transient stability of interconnected ac systems.

The use of switching type Bang-Bang controls also promises improvement to system stability subsequent to large scale disturbances, such as line faults and loss of generation and hence is investigated.

Cresap[15] et al, investigated dc power modulation using ac intertie power derivative signal to design a stabilizer capable of damping the generated negatively damped oscillation in the Pacific Intertie Scheme. This generated low frequency oscillations is due to interaction between the excitation system and dc fixed point controls.

Multi-terminal HVDC systems do not exist at present. Investigative work must however be performed to generate the required know-how before selecting them. Of necessity the investigations at this stage have to be theortical in nature and on hypothetical systems.

Concerning the stability of systems, two kinds of problems exist. First, there are large oscillations arising from major disturbances to a system such as faults of permanent nature. Studies of this kind require simulation of a non-linear system in great detail: Second, there are small oscillations started by small disturbances; e.g., minor imbalances between load and generation. If the system has negative damping the oscillations can grow and have dangerous consequences. For this class of problem it is sufficient to linearize the system about an operating point and look for analytical solutions. A system may be unstable for major faults but operates satisfactorily as long as no fault occurs. Conversely, a system which is unstable to small scale disturbance can not be operated satisfactorily because small disturbances take place in normal operation quite frequently. It is for this class of dynamic stability problem this research work is dedicated.

A safe procedure to study the effectiveness of multi-terminal HVDC networks in System Stabilization is to first use a simple model and determine the usefulness of various system states and feed back arrangements for generating a stabilizing signal which modulates the active power flow on the dc lines. Of necessity, this must be done by first finding an optimum solution and therefrom deriving sub-optimal solutions which are practical. A small signal study while taking care of one class of stability problem may also provide a good starting point for deriving stabilizer designs suitable for large disturbances.

1.2 Research Objectives

The objective of the research work is to show the