Control of a dynamic brake to reduce turbine-generator shaft transient torques
by Matthew Kenneth Donnelly

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical Engineering
Montana State University

Abstract:
The feasibility of applying a resistive dynamic brake to damp turbine shaft torsional oscillations is studied. In cases where series-compensated transmission lines increase the likelihood of subsynchronous resonance phenomena, the damping of one or more of the torsional modes of the shaft may prove to be inadequate. This is particularly so when high-speed reclosing of transmission lines near a generator is practiced. In this thesis, various control strategies and brake configurations are studied and simulation results are shown. The simulations are performed using the ElectroMagnetic Transients Program (EMTP) on models ranging from one machine, infinite bus (the IEEE Second Benchmark) to multiple machines in a complex network. A derivative of Prony's method for signal analysis is used to find a linearized transfer function of the system for controller design and implementation. Methods for reducing the complexity of the results of a Prony analysis are presented. It is seen both empirically and intuitively that a simple control law does an effective job of damping turbine shaft torques throughout the range of subsynchronous frequencies. The empirical evidence is gained through comparisons with a Generalized Predictive Control (GPC) algorithm implemented on a linearized model of the test system. Discrete-level GPC is seen to have sensitivity problems in this application. The thesis goes on to analyze and document these sensitivity problems. Recommendations are made as to size, placement, and construction of the brake for adequate damping. Studies incorporating multiple brakes are also conducted revealing that, with few exceptions, the interaction between brakes operating on non-identical machines is negligible and that the interaction between brakes operating on identical machines is substantial and desirable. Computer code for implementing a brake in the EMTP is included as an appendix.

Control of a Dynamic Brake to Reduce Turbine-Generator Shaft Transient Torques

by

Matthew Kenneth Donnelly

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Doctor of Philosophy

in

Electrical Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

November 1991

APPROVAL

of a thesis submitted by

Matthew K. Donnelly

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

Nov. 13, 1991 — Date

Roy M. Johnson — Chairman, Graduate Committee

Approved for the Major Department

Nov. 13, 1991 — Date

Head, Major Department

Approved for the College of Graduate Studies

November 14, 1991 — Date

Henry L. Parsons — Graduate Dean

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a doctoral degree at Montana State University, I agree that the Library shall make it available to borrowers under the rules of the Library. I further agree that copying of this thesis is allowable only for scholarly purposes, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for extensive copying or reproduction of this thesis should be referred to University Microfilms International, 300 North Zeeb Road, Ann Arbor, Michigan 48106, to whom I have granted "the exclusive right to reproduce and distribute copies of the dissertation in and from microfilm and the right to reproduce and distribute by abstract in any format."

Signature Matth K. Donald

Date NOVEMBER 12, 1991

ACKNOWLEDGMENTS

My sincere gratitude is extended to my thesis advisor, Dr. Roy Johnson. His faith in my abilities has motivated me in every phase of my research, and his personal friendship will be valued for many years to come. The help of Dr. Jim Smith and Dr. Don Pierre in the areas of system identification and control system design is also acknowledged. Further, I am indebted to Dr. John Lund and Dr. Ken Bowers for sparking in me an intense interest in the mathematical sciences which will stay with me forever.

In addition to the funding provided by the Electric Power Research Institute, I would like to acknowledge the financial contributions made by the Montana Electric Power Research Affiliates (MEPRA) and the Montana State University Engineering Experiment Station (EES). The guidance provided by my industrial advisors is also appreciated. Mr. Ray Brush of Montana Power Company supplied me with much needed practical information. Dr. John Hauer of Bonneville Power Administration provided insight at our meetings and has been an inspiration in developing some system identification routines.

Lastly, I would like to thank my fiance', Toni Crosby, for enduring the long days and late nights associated with graduate study. Her interest in the work and her support and understanding have made this research enjoyable.

TABLE OF CONTENTS

LIST OF TABLES vii

LIST OF FIGURES viii

NOMENCLATURE xi

ABSTRACT xii

1. INTRODUCTION 1

History Of The Problem 2
Description Of The Problem 3
Pertinent Literature 7

2. MODELS AND MODELING 10

The MPC Colstrip Model 12
The Dynamic Brake 15
Implementation Of The Brake In EMTP 16
An Alternative Integration Technique for Time-Domain Simulation 20

3. SYSTEM ANALYSIS TECHNIQUES 24

Frequency Scan 24
Electromagnetic Transients Program (EMTP) 28
Eigenvalue Analysis 29
System Identification And Modeling 29
Output Analysis of Prony Identification Routine 32

4. CONTROLLER DESIGN 39

Straight Feedback Control 41
Filtering The Feedback Signal 46
Optimal Control 48
Sensitivity Problems with Discrete-Level GPC 51
Sizing The Brake 66

TABLE OF CONTENTS -- Continued

5. SIMULATION RESULTS 70

Effects Of Filtering 71
Results With A 200 MW Brake 75
Effects Of Brake Size 77
Damping Electromechanical Modes 80
Thyristor Types 82
Effects Of Braking On Nearby Machines 84

6. EFFECTS OF FAULT TYPE, POWER FACTOR, AND BRAKE ORGANIZATION 87

Multiple Brakes At A Single Location 94
A Single Brake For Multiple Machines 97

7. CONCLUSIONS AND FUTURE WORK 101

REFERENCES CITED 109

APPENDICES 116

A-IEEE SECOND SUBSYNCHRONOUS BENCHMARK DATA .. 117
B-SYSTEM DATA FOR MULTI-MACHINE SIMULATIONS .. 122
C-EMTP INTERFACE AND CONTROLLER CODE 142
D-ADAMS PREDICTOR-CORRECTOR TO IMPLEMENT A PASC SYSTEM 147

LIST OF TABLES

Table Page

1. Prony Analysis Results for Example System 35

LIST OF FIGURES

Figure		Page
1.	The IEEE Second Subsynchronous Benchmark	11
2.	MPC Colstrip Model	14
3.	Wye Connected Dynamic Brake	15
4.	Dynamic Brake With Type 60 Sources	17
5.	EMTP Calls To Control Subroutine	20
6.	Frequency Scan From Colstrip #1	26
7.	Frequency Scan From Colstrip #3	27
8.	Eigenvalues of the MPC System From Colstrip #3	31
9.	Errors Between Actual and Estimated Response for the System in (3.4)	36
10.	Root Locus of the MPC Colstrip Test System at Colstrip #3 Using Generator $\Delta\omega$ as a Feedback Signal	42
11.	Root Locus of the MPC Colstrip Test System at Colstrip #3 Using Generator Acceleration as a Feedback Signal	44
12.	Root Locus of the MPC Colstrip Test System at Colstrip #3 Using High Pressure Turbine $\Delta\omega$ as a Feedback Signal	45
13.	Root Locus of the MPC Colstrip Test System at Colstrip #3 Using the Filtered Generator $\Delta\omega$ as a Feedback Signal	47
14.	Uncontrolled Response of System Due to Pulse Disturbances	66
15.	Damping of System From Feedback Gain and GPC ..	66

LIST OF FIGURES -- Continued

Figure Page

16. Second Benchmark Generator Speed Deviation 67

17. Second Benchmark Gen-LP Torque 67

18. Uncontrolled Generator $\Delta\omega$ for Three Phase Fault with Reclose 73

19. Filtered and Unfiltered Controlled Response for Case in Figure 18 73

20. Generator Speed Deviation and Brake Current for Unfiltered Controller 74

21. Generator Speed Deviation and Brake Current for High-Pass Filtered Controller 74

22. LP1-LP2 Torque for Disturbance in Figure 18 Showing Effect of Filtering 75

23. HP-IP Torque for Disturbance in Figure 18 76

24. LP2-Gen Torque for Disturbance in Figure 18 ... 77

25. LP1-LP2 Torque for Disturbance in Figure 18 Using 800 MW Brake 79

26. HP-IP Torque for Disturbance in Figure 18 Using 800 MW Brake 80

27. Generator $\Delta\omega$ Signals Showing the Electromechanical Mode Damping 82

28. Generator $\Delta\omega$ Signals Showing the Effect of Thyristor Type 83

29. Colstrip #1 Uncontrolled Generator Speed Deviation 85

30. Colstrip #1 Generator Speed Deviation for 200 MW and 800 MW Brake 85

31. FFT of Generator $\Delta\omega$ 89

32. FFT of HP-IP Torque 89

LIST OF FIGURES -- Continued

Figure | Page

33. FFT of IP-LP1 Torque 89

34. FFT of LP1-LP2 Torque 89

35. FFT of LP2-Gen Torque 90

36. Generator $\Delta\omega$ Signals Showing Damping of SLG Fault 91

37. LP1-LP2 Torque Showing Damping of SLG Fault ... 92

38. LP2-Gen Torque Showing Damping of SLG Fault ... 93

39. Colstrip #3 $\Delta\omega$ Signals Showing Damping for Multiple Brakes at a Single Location 95

40. Colstrip #1 $\Delta\omega$ Signals Showing Damping for Multiple Brakes at a Single Location 96

41. Colstrip #3 LP1-LP2 Torque Showing Damping for Multiple Brakes at a Single Location 96

42. Colstrip #1 LP-Gen Torque Showing Damping for Multiple Brakes at a Single Location 97

43. Colstrip #3 $\Delta\omega$ Signals Showing Damping for a Single Brake on Multiple Machines 98

44. Colstrip #1 $\Delta\omega$ Signals Showing Damping for Multiple Brakes at a Single Location 99

45. EMTP Data File for IEEE Benchmark 118

46. EMTP Data File for Multi-Machine System 123

47. Controller Subroutine INJECT 143

48. Modifications to the EMTP Subroutine CSUP 144

49. Adams Predictor-Corrector for Experimental PASC System 148

50. File to Execute the Integration Routine of Figure 49 165

NOMENCLATURE

$\mathcal{L}\mathbf{f}$	The LaPlace transform of **f**
$\mathcal{L}^{-1}\mathbf{g}$	The inverse LaPlace transform of **g**
$\lVert \; \rVert$	Any induced matrix norm
$\kappa(A)$	The condition number of A
B^{+}	The Moore-Penrose Inverse of B
Q^{H}	The conjugate-transpose of Q

ABSTRACT

The feasibility of applying a resistive dynamic brake to damp turbine shaft torsional oscillations is studied. In cases where series-compensated transmission lines increase the likelihood of subsynchronous resonance phenomena, the damping of one or more of the torsional modes of the shaft may prove to be inadequate. This is particularly so when high-speed reclosing of transmission lines near a generator is practiced. In this thesis, various control strategies and brake configurations are studied and simulation results are shown. The simulations are performed using the ElectroMagnetic Transients Program (EMTP) on models ranging from one machine, infinite bus (the IEEE Second Benchmark) to multiple machines in a complex network. A derivative of Prony's method for signal analysis is used to find a linearized transfer function of the system for controller design and implementation. Methods for reducing the complexity of the results of a Prony analysis are presented. It is seen both empirically and intuitively that a simple control law does an effective job of damping turbine shaft torques throughout the range of subsynchronous frequencies. The empirical evidence is gained through comparisons with a Generalized Predictive Control (GPC) algorithm implemented on a linearized model of the test system. Discrete-level GPC is seen to have sensitivity problems in this application. The thesis goes on to analyze and document these sensitivity problems. Recommendations are made as to size, placement, and construction of the brake for adequate damping. Studies incorporating multiple brakes are also conducted revealing that, with few exceptions, the interaction between brakes operating on non-identical machines is negligible and that the interaction between brakes operating on identical machines is substantial and desirable. Computer code for implementing a brake in the EMTP is included as an appendix.

CHAPTER 1

INTRODUCTION

The primary focus of this thesis is the damping of transient torques in turbine-generator shafts following electrical network system disturbances. The damping is to be improved by means of a dynamic resistive brake located near to the generator. Transient torques are oscillatory in nature. It is desirable to damp these oscillations as quickly as possible, particularly in the case where high speed reclosing is employed on transmission lines emanating from the generator.

This dissertation contains seven chapters. Chapter 1 is an introduction to the problem along with a brief history and literature review. Chapter 2 describes the models used in the research and the associated modeling techniques. Because of the complexity of the electrical network and the cost of lost generation, accurate and realistic modeling is a crucial task. Therefore, a significant amount of work was spent in developing appropriate models and simulation routines. This effort should prove to be a great benefit to other researchers in this area. Chapter 3 discusses some of the techniques that are useful in the analysis of subsynchronous resonance problems. Specifically, the analysis techniques used in determining appropriate feedback signals for the dynamic brake and for sizing the brake are explained. Chapters 4 and 5 describe the control techniques, controller analysis and simulation results. In Chapter 6, some special cases are examined to determine the effectiveness of the control algorithm over a wide range of conditions. Finally, Chapter 7 offers some conclusions relating to the project and provides some direction for future work. Following Chapter 7, a list of references is provided.

In addition to the text, four appendices are included showing some representative computer code used in this research. Appendices A and B contain data files for the "IEEE Second Subsynchronous Benchmark" model and the Montana Power Company Colstrip model. Appendix C shows the interface and controller subroutines. Appendix D contains computer code implementing a numerical integration technique along with a sample data file described in Chapter 2.

History of the Problem

The notion of series compensation to increase the carrying capacity in electric power transmission lines beyond what is considered the uncompensated stability limit was developed almost simultaneously with the widespread adoption of alternating current as the transmission standard in the US.

Dr. Charles Concordia recognized as early as 1937 that series compensation would set up a resonance in the electrical network and that this was a potential problem [1]. Dr. Concordia and other early researchers saw this resonance as a problem only with respect to the electrical network. It was not until 33 years later when a turbine-generator was actually damaged in operation that researchers began to look at the interaction between the electrical network and the turbine-generator shaft mechanical system.

In 1970, the first of two shaft failures occurred at the Mohave plant in southern Nevada. By 1972, a consortium of engineers had determined that the cause of the 1970 shaft failure and the second failure in 1971 were due to interactions between the electrical network and the mechanical system at certain frequencies where both systems showed a tendency to resonate [2], [3]. This phenomenon has been the topic of much research since that time.

Description of the Problem

Power system network disturbances create several distinct transients in nearby generation units. One such transient occurs in steam-driven generators as the separate masses along the turbine-generator (TG) shaft oscillate against each other. The magnitude of the inertias of these masses along with the spring constant of the connecting shaft determine the frequencies of oscillation according to Newtons Law for torsional mechanics,

$$Torque = Inertia x angular acceleration.$$

Current technology in the field of turbine design is such that these natural frequencies of oscillation fall into the range of 10 to 50 Hertz. Power system transmission networks are relatively poorly damped at frequencies below synchronous speed. In some cases the combination of the network and turbine shaft resonances at a frequency can be negatively damped. It is this interaction between the poorly damped network and the turbine shaft natural frequencies that has been described as *Subsynchronous Resonance* or SSR.

The phenomena of subsynchronous resonance can be divided into two main areas for the purpose of analysis. These are generally recognized in the literature as being self-excitation phenomena and transient torque phenomena. The area of self-excitation effects is often further divided into induction motor effects and torsional interactions. In the cases that have been reported, both conditions occur simultaneously [4]. From a control perspective self-excitation phenomena is not a separate issue from transient torque phenomena but rather the issue is how these electrical and mechanical interactions affect the damping of turbine shaft oscillations. A shaft system with very low or no damping will exhibit steady-state instability. A system with larger damping factors for each natural mode will not exhibit steady state oscillations, but may experience damaging shaft torques for a given sequence of network events.

The practice of transmission line high-speed reclosing may fatigue some turbine-generator shaft systems [5], [6]. Although the shaft is sufficiently damped so as to prevent steady state oscillation, the damping factors are small enough that damaging shaft torques can be created by a high speed reclosing operation. A system with natural modes of oscillation will always respond more actively to inputs that contain frequencies near to the natural modes. High-speed reclosing involves faster operation of breakers which necessarily means creating shocks to a shaft system that contain a larger amount of energy at frequencies nearer to the natural shaft modes.

Generator shaft torsional damping results from both mechanical and electrical factors. The mechanical factors include windage, bearing friction, and natural damping of the shaft material. The windage on turbine blades is cited as the major factor which causes shaft systems to exhibit more damping at higher machine loadings [7]. Electrical factors contributing to damping are predominated by the electrical resonance points of the network. Maintaining a high electrical impedance at all frequencies within the SSR range will eliminate problems of steady state shaft oscillations but may not be sufficient to produce enough damping to safely allow for high speed reclosing. This may be an important consideration for a control strategy which is intended to produce enough damping to allow for high speed reclosure. Such a strategy will likely have to provide much more damping than would be obtained passively by changing the apparent network impedance over the range of subsynchronous frequencies.

It is also important to realize that during a typical short circuit disturbance with fault clearing and reclosing, the generator shaft system is exposed to three suddenly different electrical networks. These correspond to the apparent impedances seen during the short, those seen during clearing and those seen upon reclosure. These three networks are very likely to have different resonant characteristics and result in different damping factors for each of the shaft natural modes. With this in mind a controller that will produce good damping must be able to operate on the shaft system during as much of these three time periods as possible.

This study examines the use of a resistive brake at the terminals of a large synchronous generator which is activated in such a way and at such a time so as to provide additional damping to the turbine-generator shaft during critical transients. Only steam-powered generators (thermal units) are considered since hydro-electric generators do not exhibit mechanical oscillations in the frequency range of concern for this work.

Pertinent Literature

There is an abundance of literature dealing with the topic of subsynchronous resonance. The vast majority of these papers treat SSR as a sustained phenomenon and do not discuss the transient torque problem associated with turbine-generator shaft fatigue. The reader is referred to the IEEE working group bibliographies on SSR for an exhaustive list of references in this area [8]-[11]. The IEEE working group has also published a reference of terms, definitions, and symbols relating to SSR phenomena [12]. In [13], Bowler gives a concise summary of the various aspects of SSR that will provide the reader with a familiarity of the topic without thorough research. In his text on power system dynamics [14], Yu also gives an excellent summary. Hamouda, Iravani, and Hackam give insight into the specific problem of torsional oscillations and provide an integrated study model in [15]. Agrawal, et al., [16], explain some of the evaluation tools available to researchers in this field.

Several papers have investigated the use of braking technologies to improve power system stability in the "transient stability" sense. Traditionally, transient stability has referred to the ability of synchronous generators to return to the system synchronous frequency following a major disturbance. In [17], [18], and [19], some optimal control strategies are developed to damp low frequency swings using braking resistors. These strategies are implemented in computer simulations to evaluate their effectiveness. Yoshida's work, [20], is more functional in that he discusses some implementation issues with respect to resistive devices in the network. A resistive brake acting alone may not provide the optimal amount of damping in transient stability studies. The coordination of system components such as exciters with a braking resistor is discussed in [21]. Of equal interest to the theoretical studies, the testing of braking resistors on the actual system is always enlightening. In [22] and [23], the results of testing at two sites which have installed large braking resistors are discussed.

Additionally, several methods have been proposed to address the problem of damping transient torques in TG shafts. Hingorani, et al. discuss the possibility of using a series device to damp transient torques [24], [25]. The referenced device appears to be better suited for damping the sustained oscillations commonly associated with severe SSR. In [26], the generator field is adjusted to attempt to compensate for torsional oscillations with some success. The use of a resistive brake to damp higher frequency oscillations such as can be seen in the mechanical mass-spring system of a turbine shaft was first researched at Purdue University [27], [28]. No other recent literature has been found dealing specifically with this topic. Generally, the brake size may be smaller than would be seen in a brake designed to improve transient stability, but expensive thyristors must be used to switch the brake. The low frequencies involved in traditional transient stability studies allow the use of circuit breakers to switch these resistors.

CHAPTER 2

MODELS AND MODELING

The development, testing and verification of models and modeling techniques make up a large percentage of the work performed in this research. This chapter provides the documentation for the two test systems that were developed for use in the study of transient torque. The information provided herein should be useful as a starting point in any future studies involving turbine-generator shaft oscillations and the transient torque phenomena.

A one-line diagram of the first test system examined is shown in Figure 1. The basis for this model is the IEEE Second Subsynchronous Benchmark case as reported in [29]. This system provides a benchmark by which all studies in this area can be compared. The machine and line parameters found in the paper are implemented in an Electromagnetic Transients Program (EMTP) [32], [34], [37]. The damping factors for the generator shaft system in this study have been increased over what is specified for a self-excitation case. The actual damping values used are as specified in [29] under the section titled "Torque Amplification Studies." The IEEE First

Subsynchronous Benchmark [30] was not deemed to be suitable for these studies because the authors made no provision for simulating transient SSR (torque) problems.

The Second Subsynchronous Benchmark model is useful in testing various control strategies on a single machine system and in comparing the effectiveness of one control technique over another. The system is fairly simple and as an IEEE benchmark it can lend credibility to simulation results. The basic EMTP data file used to implement this benchmark is shown in Appendix A.

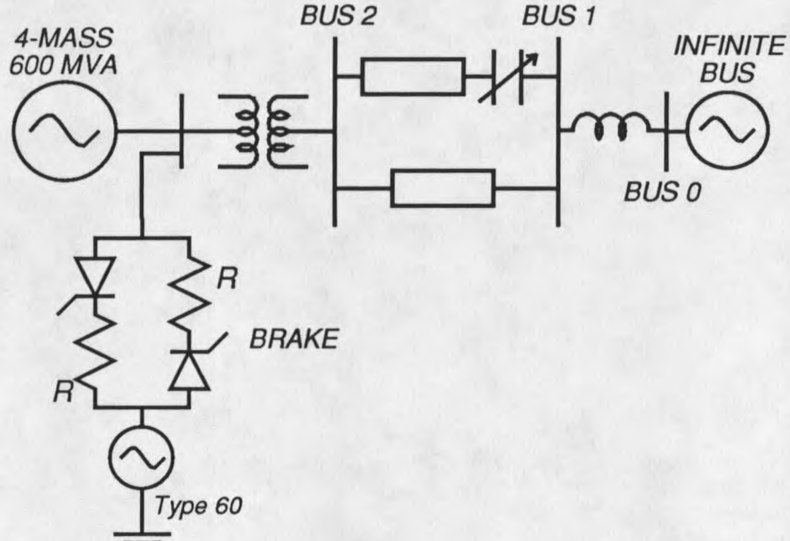

Figure 1. The IEEE Second Subsynchronous Benchmark.

A second test system developed for the braking studies is the Montana Power Company (MPC) Colstrip Model and associated 500 kV transmission lines. This system has several advantages over the benchmark system which make it more useful as the primary test bed for the dynamic brake stability studies presented here. The basis for the model was provided by Ray Brush of MPC in late 1989. Though significantly modified from the original MPC data for the purposes of this study, the current model has retained enough major features of the original to make it a realistic facsimile.

The MPC Colstrip Model

Three major modifications to the original model stand out as being significant. They are: 1) the inclusion of the J. Marti line models [31] on the 500 kV lines replacing Π sections, 2) the elimination of the zinc oxide varistors used as series capacitor protection, and 3) creation of Thevenin equivalents at the 230 kV buses and at Dworshack and Bell substations. Numerous other less dramatic changes were made in converting the files to EMTP version 2.0 and tuning the simulations. The current model is well suited to studies on transient torque and dynamic braking. A one-line diagram of the system is shown in Figure 2. The Colstrip generators appear on the right as synchronous machines and are labeled *SM*.

The model, implemented in the Electric Power Research Institute's (EPRI's) version of EMTP, consists of two sets of two identical turbine-generators for a total of four machines at the generating facility. Two machines, Colstrip #1 and Colstrip #2, feed a 230 kV bus located at Colstrip and are each rated at 377 MVA. An autotransformer then feeds the 500 kV bus at Colstrip from the 230 kV bus. These are three mass machines. The masses consist of two turbines and a generator. Colstrip #3 and Colstrip #4 are two larger machines, each rated at 818 MVA, that feed the 500 kV bus at Colstrip directly. These are six mass machines consisting of four turbines, a generator, and an exciter.

The machines can be configured in several different ways depending on the type of study desired. One common configuration in the preliminary studies was to combine the two large units into one 1636 MVA conglomerate machine and implement the brake at the terminals of this machine. In previous studies on the topic, the case with multiple machines -- particularly closely coupled machines -- has not been considered.

The bulk of the energy from Colstrip is carried on twin 500 kV circuits, both of which are series compensated. The series compensation can provide a turbine-generator mass-spring system with negative damping under certain circumstances as identified in numerous papers on SSR. In almost all cases, the presence of series compensation on a transmission line has the effect of reducing the damping of at least one mode of a turbine-generators natural frequencies

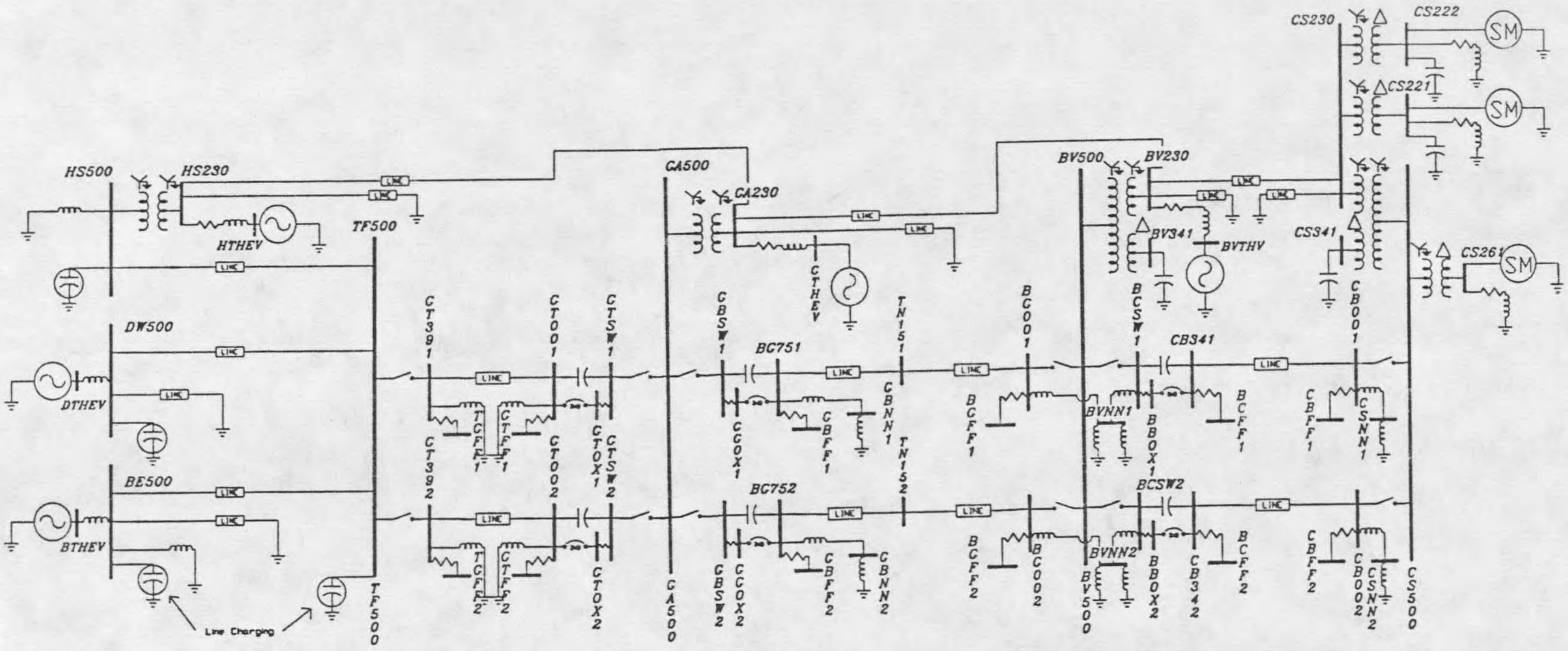

Figure 2. MPC Colstrip Model

of oscillation. This reduction in damping can in turn create problems with transient torques in turbine-generator shafts following system disturbances. Again, the Purdue studies do not incorporate series compensation into their systems for studying transient torques.

The basic EMTP data file for the MPC Colstrip model is included in Appendix B.

The Dynamic Brake

The resistive brake is connected to the system in wye at the generator terminals. The wye connected brake is shown in Figure 3.

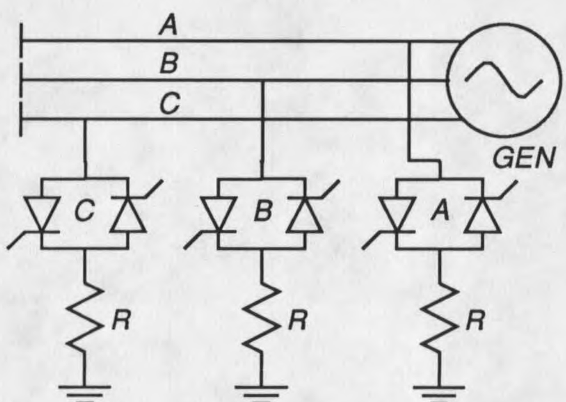

Figure 3. Wye Connected Dynamic Brake.

Historically, resistive brakes have been placed at higher voltages than is seen at the terminals of a synchronous machine. The Peace River 600 MW brake is at 138 kV [22] and the BPA 1400 MW brake is at 230 kV [23]. Since the primary function of these devices has been for improving transient stability, they are large and employ circuit breakers as switching devices. The brake presented here utilizes thyristors as switching devices, and so a lower operating voltage may be considered advantageous. Circuit breakers may still be employed in a normally closed position to protect the system against thyristor failure.

The size of the brake is determined by the value of resistance. In this study, brakes ranging from 41 MW to 850 MW were used. It is difficult to put a percent rating on these values when dealing with multiple machines, however 850 MW is approximately 50% of the conglomerate Colstrip machine rated MVA.

Implementation of the Brake in EMTP

The brake is implemented in the EMTP as shown in Figure 4. The EMTP Type 60 sources connected in each phase to ground are TACS controlled sources. TACS is a sub-program of the EMTP that implements controllers on the simulated systems [32]. TACS is an acronym for Transient Analysis of Control Systems. In this case, these sources are always proportional to the voltage at their respective generator terminals. The relationship between the generator bus voltage and the Type