AN ADAPTIVE SHORT-TIME COMPENSATION SCHEME FOR IMPROVING POWER SYSTEM STABILITY

A Thesis Submitted to the College of Graduate Studies and Research
in Partial Fulfillment of the Requirements
for the Degree of
Master of Science
in the
Department of Electrical Engineering
University of Saskatchewan
Saskatoon

By

SALEH HUMMOOD ABDU-ALLAH AL-SENAIDI

Spring 2001

All rights reserved.
PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a Postgraduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis work or, in their absence, by the Head of the Department or the Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis.

Requests for permission to copy or to make other use of material in this thesis in whole or part should be addressed to:

Head of the Department of Electrical Engineering
University of Saskatchewan
57 Campus Drive
Saskatoon, Saskatchewan S7N 5A9
Canada
AN ADAPTIVE SHORT-TIME COMPENSATION SCHEME FOR IMPROVING POWER SYSTEM STABILITY

Candidate: Saleh Al-Senaidi
Supervisor: Dr. Sherif O. Faried

Master of Science Thesis presented to the College of Graduate Studies and Research
Spring 2001

ABSTRACT

Successful operation of a power system depends largely on the engineer’s ability to provide reliable and uninterrupted service to the loads. The reliability of a power system supply implies much more than merely being available. Ideally, the loads must be fed at constant voltage and frequency at all times. The first requirement of reliable service is to keep the synchronous generators running in parallel and with adequate capacity to meet the load demand. Maintaining such an operation and dealing with its problems fall under the heading of “power system stability.”

This thesis presents an adaptive short-time compensation and reclosing technique for improving power system transient stability. The fundamental concept of such a technique is to interrupt unsymmetrical faults, namely line-to-line, single and double line-to-ground faults on double-circuit transmission lines using selective-pole switching. The transmission system is then balanced using Thyristor Controlled Series Capacitors in the interrupted phases. Adaptive selective-pole reclosing is then used for reclosing the tripped phase(s).

To explore the effectiveness of the proposed adaptive short-time compensation and reclosing technique, investigations are carried out on a sample multi-machine power system through time simulations using the EMTP.
The results of these investigations have shown that the proposed technique is effective in enhancing the transient stability of the power system by restoring the transmission system capacity immediately after fault clearing. It has been also shown that the utilization of adaptive selective-pole reclosing would eliminate the possibility of reclosing the tripped phase(s) into a permanent fault. The thesis also discusses the possibility of adding a further improvement to the system stability by boosting the transmission system capacity using TCSC.
ACKNOWLEDGMENT

The author would like to extend his sincere gratitude appreciation to his supervisor, Dr. S. O. Faried, for his valuable guidance, assistance, patience, helpful suggestions and friendly supervision throughout the course of this work and preparation of this thesis.

The author would like to extend his heartfelt gratitude to his parents, brothers, sisters and relatives for their constant encouragement and support.

The author would like to acknowledge the friendship and assistance of professors, technicians, secretaries and fellow graduate students within the Department of Electrical Engineering.

The author would like to thank his friends who assisted him in the preparation of this work.

Finally, financial support provided by the Government of Saudi Arabia in the form of a graduate scholarship is thankfully acknowledged.
Dedicated to My Parents
# TABLE OF CONTENT

PERMISSION TO USE i

ABSTRACT ii

ACKNOWLEDGMENT iv

DEDICATION v

TABLE OF CONTENTS vi

LIST OF TABLES ix

LIST OF FIGURES x

LIST OF SYMBOLS xvi

1. INTRODUCTION 1

1.1 Power System Stability: Basic Concepts and Definitions 1

1.1.1 Rotor Angle Stability 2

1.1.1.1 Synchronous Machine Characteristics 2

1.1.1.2 Power versus angle relationship 3

1.1.2 The Stability Phenomena 6

1.2 Methods of Improving Transient Stability 9

1.2.1 High-Speed Fault Clearing 10

1.2.2 Reduction of Transmission System Reactance 10

1.2.3 Regulated Shunt Compensation 12

1.2.4 Dynamic Braking 12

1.2.5 Reactor Switching 13

1.2.6 Independent-Pole Operation of Circuit Breakers 14

1.2.7 Single-Pole Switching 14

1.2.8 Steam Turbine Fast-Valving 15

1.2.9 Generator Tripping 15

1.2.10 Controlled System Separation and Load Shedding 16

1.2.11 High-Speed Excitation Systems 16

1.3 Objective of the Thesis 17

1.4 Outline of the Thesis 17
LIST OF TABLES

Table 4.1: Voltages of unenergized phases during single phase energization of a transposed transmission line (line voltage: 765 kV, energized phase: A, \(|V_A| = 1.0 \text{ p.u.}\)).

Table A.1: Synchronous generator data.

Table A.2: Transmission line data.
LIST OF FIGURES

Figure 1.1: Power transfer characteristic of a two-machine system: (a) single-line diagram, (b) idealized model, (c) phasor diagram, (d) power-angle curve. 5

Figure 1.2: Types of rotor angle instabilities: (a) aperiodic, (b) oscillatory. 8

Figure 1.3: Controlled braking resistor bank. 13

Figure 1.4: Braking resistors for unbalanced ground faults. 14

Figure 2.1: System under study. 20

Figure 2.2: Stator and rotor circuits of a synchronous machine. 21

Figure 2.3: Modeling of the synchronous machine in the d-q-0 reference frame. 22

Figure 2.4: Modeling of transmission line. 23

Figure 2.5: Fault clearing process modeling: (a) three-phase fault, (b) three-phase-to-ground fault. 25

Figure 3.1: Fault locations on the system under study. 28

Figure 3.2: Generator electromagnetic torques, stator currents and voltages, rotor currents, speeds and load angles during a 4-cycle three-phase fault at F1. 31

Figure 3.3: Generator electromagnetic torques during successful reclosing of a 4-30 cycle three-phase fault at F1. 36
Figure 3.4: Generator speeds and load angles during a 4-cycle three-phase fault at F1 (without reclosing, with a 30-cycle successful reclosing).

Figure 3.5: High-speed reclosing of a single line-to-ground fault: (i) fault; (ii) isolation of the fault; (iii) successful reclosure; (iv) unsuccessful reclosure, (a) triple-pole reclosing, (b) single-pole reclosing.

Figure 3.6: Generator electromagnetic torques, speeds and load angles during successful triple-pole reclosing of a 4-45 cycle single line-to-ground fault at F2.

Figure 3.7: Generator electromagnetic torques and rotor currents during successful single-pole reclosing of a 4-45 cycle single line-to-ground fault at F2.

Figure 3.8: Generator speeds and load angles during successful reclosing of a 4-45 cycle single line-to-ground fault at F2 (triple-pole switching, single-pole switching).

Figure 3.9: Selective pole switching of line-to-line and double line-to-ground faults: (i) fault; (ii) isolation of the fault; (iii) successful reclosure; (iv) unsuccessful reclosure, (a) line-to-line fault, (b) double line-to-ground fault.

Figure 3.10: Generator electromagnetic torques during successful reclosing of a 4-45 cycle line-to-line fault at F2: (a) triple-pole reclosing, (b) selective-pole reclosing.

Figure 3.11: Generator speeds and load angles during successful reclosing of a 4-45 cycle line-to-line fault at F2 (triple-pole reclosing, selective-pole reclosing).

Figure 3.12: Selective-pole switching of a line-to-line fault by interrupting only one of the faulted phases: (a) during fault, (b) after fault clearing.

Figure 3.13: Generator speeds and load angles during successful reclosing of a 4-45 cycle line-to-line fault at F1.

Figure 4.1: Thyristor controlled series capacitor model.

Figure 4.2: One TCSC module power circuit.
Figure 4.3: Blocked and bypass operating modes: (a) thyristors blocked (no thyristor current), (b) thyristor-bypassed (full thyristor conduction).

Figure 4.4: Vernier operating modes with partial thyristor conduction: (a) capacitive vernier operation, (b) inductive vernier operation.

Figure 4.5: Typical TCSC X-I capability characteristic.

Figure 4.6: Principle of adaptive short-time compensation scheme.

Figure 4.7: Transmission system equivalent circuit during adaptive short-time compensation of a line-to-line or double line-to-ground fault.

Figure 4.8: Principle of adaptive reclosing.

Figure 4.9: Induced voltages during adaptive reclosing.

Figure 4.10: Reclosing logic for identification system status during adaptive selective-pole reclosing of a transmission line (unfaulted phase: C).

Figure 4.11: Induced voltages during single-pole reclosing.

Figure 4.12: Adaptive single-pole reclosing logic.

Figure 4.13: Principle of the adaptive short-time compensation and reclosing scheme.

Figure 5.1: System under study with the TCSC banks.

Figure 5.2: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G_1 during unsuccessful reclosing of a 4-30-4 cycles line-to-line fault on line L_2 at F_1: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.

Figure 5.3: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G_1 during successful reclosing of a 4-30 cycles line-to-line fault on line L_2 at F_1: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure 5.4: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G\textsubscript{1} during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L\textsubscript{2} at F\textsubscript{1}: (a) single-pole switching, (b) adaptive short-time compensation and reclosing.

Figure 5.5: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G\textsubscript{1} during successful reclosing of a 4-30 cycles single line-to-ground fault on line L\textsubscript{2} at F\textsubscript{1}: (a) single-pole switching, (b) adaptive short-time compensation and reclosing.

Figure 5.6: Transmission system (L\textsubscript{4}, L\textsubscript{5}, L\textsubscript{6}, L\textsubscript{7}) equivalent circuit during adaptive short-time compensation of simultaneous single and double line-to-ground faults.

Figure 5.7: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G\textsubscript{2} during unsuccessful reclosing of a 4-30-30 cycles single line-to-ground fault on line L\textsubscript{6} at F\textsubscript{4} and line-to-line fault on line L\textsubscript{4} at F\textsubscript{3}: (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.

Figure 5.8: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G\textsubscript{2} during successful reclosing of a 4-30 cycles single line-to-ground fault on line L\textsubscript{6} at F\textsubscript{4} and line-to-line fault on line L\textsubscript{4} at F\textsubscript{3}: (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.

Figure 5.9: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G\textsubscript{1} during unsuccessful triple-pole reclosing of a 4-30-4 cycles line-to-line fault on line L\textsubscript{2} at F\textsubscript{1} and a false 4-cycle three-pole tripping of line L\textsubscript{1} with no reclosing: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.

Figure 5.10: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G\textsubscript{1} during successful triple-pole reclosing of a 4-30 cycles line-to-line fault on line L\textsubscript{2} at F\textsubscript{1} and a false 4-cycle three-pole tripping of line L\textsubscript{1} with no reclosing: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure 5.11: Transmission system (L1&L2) equivalent circuit for the case of boosting the transmission capacity during adaptive short time compensation of a line-to-line fault.

Figure 5.12: Generator load angle responses during successful adaptive short-time compensation and reclosing of a 4-30 cycles line-to-line fault on line L3 at F1 and a false 4-cycle three-pole tripping of line L1 with no reclosure.

Figure A.1: System load flow (bus voltages are in p.u.).

Figure C.1: Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles double line-to-ground fault on line L2 at F1: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.

Figure C.2: Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles double line-to-ground fault on line L2 at F1: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.

Figure C.3: Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L6 at F4 (phase C) and a 4-30-4 cycles line-to-line fault on line L4 at F3 (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.

Figure C.4: Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles single line-to-ground fault on line L6 at F4 (phase C) and a 4-30 cycles line-to-line fault on line L4 at F3 (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.

Figure C.5: Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L6 at F4 (phase C) and a 4-30-4 cycles double line-to-ground fault on line L4 at F3 (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.6: Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30 cycles double line-to-ground fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>a, b, c</td>
<td>stator phase windings</td>
<td></td>
</tr>
<tr>
<td>A, B, C</td>
<td>phases A, B, C</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>capacitance</td>
<td></td>
</tr>
<tr>
<td>C.B.</td>
<td>circuit breaker</td>
<td></td>
</tr>
<tr>
<td>CB1, CB2</td>
<td>circuit breaker number 1 and 2</td>
<td></td>
</tr>
<tr>
<td>CCP</td>
<td>common control and protection</td>
<td></td>
</tr>
<tr>
<td>e_a, e_b, e_c</td>
<td>instantaneous stator phase to neutral voltages of phases a, b, c</td>
<td></td>
</tr>
<tr>
<td>e_d</td>
<td>instantaneous d-axis voltage</td>
<td></td>
</tr>
<tr>
<td>e_fd</td>
<td>field voltage</td>
<td></td>
</tr>
<tr>
<td>e_q</td>
<td>instantaneous q-axis voltage</td>
<td></td>
</tr>
<tr>
<td>e_0</td>
<td>instantaneous 0-sequence voltage</td>
<td></td>
</tr>
<tr>
<td>EG</td>
<td>generator internal voltage</td>
<td></td>
</tr>
<tr>
<td>EM</td>
<td>motor internal voltage</td>
<td></td>
</tr>
<tr>
<td>ET1</td>
<td>generator terminal voltage</td>
<td></td>
</tr>
<tr>
<td>ET2</td>
<td>motor terminal voltage</td>
<td></td>
</tr>
<tr>
<td>EHV</td>
<td>Extra High Voltage</td>
<td></td>
</tr>
<tr>
<td>EMTP</td>
<td>Electromagnetic Transient Program</td>
<td></td>
</tr>
<tr>
<td>FACTS</td>
<td>Flexible AC Transmission Systems</td>
<td></td>
</tr>
<tr>
<td>F_k</td>
<td>fault location, where k = 1, 2, 3, 4</td>
<td></td>
</tr>
<tr>
<td>fd</td>
<td>field winding</td>
<td></td>
</tr>
<tr>
<td>G_k</td>
<td>generator number k, where k = 1, 2, 3</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>inertia constant in seconds</td>
<td></td>
</tr>
<tr>
<td>i_a, i_b, i_c</td>
<td>instantaneous stator currents in phases a, b, c</td>
<td></td>
</tr>
</tbody>
</table>
\( i_{ab}, i_{bb}, i_{ck} \)  

- instantaneous stator currents of generator \( G_k \) in phases \( a, b, c \), where \( k = 1, 2, 3 \)

\( i_d \)  

- instantaneous \( d \)-axis current

\( i_{fd} \)  

- field circuit current

\( i_q \)  

- instantaneous \( q \)-axis current

\( i_0 \)  

- instantaneous \( 0 \)-sequence current

\( i_{1d} \)  

- \( d \)-axis amortisseur circuit current

\( i_{1q} \)  

- \( q \)-axis first amortisseur circuit current

\( i_{2q} \)  

- \( q \)-axis second amortisseur circuit current

\( i_{fdk}, i_{1dk}, i_{1gk}, i_{2gk} \)  

- currents of rotor circuits of generator \( G_k \), where \( k = 1, 2, 3 \)

\( I \)  

- line current

\( I_C \)  

- capacitor current

\( I_{Line} \)  

- line current

\( I_T \)  

- thyristor current

\( I_{rated} \)  

- rated current of TCSC

\( j \)  

- \( \sqrt{-1} \)

\( L_{ad} \)  

- \( d \)-axis magnetizing inductance

\( L_{aq} \)  

- \( q \)-axis magnetizing inductance

\( L_{ffd} \)  

- self-inductance of the field winding

\( L_{f1d} \)  

- mutual inductance between field winding and \( d \)-axis amortisseur winding

\( L_I \)  

- armature leakage inductance

\( L_L \)  

- transmission line equivalent inductance per phase

\( L_S \)  

- small inductance in series with thyristor

\( L_{11d} \)  

- self-inductance of \( d \)-axis amortisseur winding

\( L_{11q} \)  

- self-inductance of \( q \)-axis first amortisseur winding

\( L_{22q} \)  

- self-inductance of \( q \)-axis second amortisseur winding

\( L_0 \)  

- \( 0 \)-sequence linkage inductance

\( L_k \)  

- transmission line number \( k \), where \( k = 1, 2, ..., 9 \)

MCP  

- module control and protection
\( P \) deferential operator \((\frac{d}{dt})\)

\( P \) electrical power

\( P_{\text{max}} \) maximum electrical power

\( R_a \) armature resistance

\( R_{\text{fd}} \) field winding resistance

\( R_g \) resistor connected between the ground and the neutral of the Y-connected high-voltage winding of the generator step-up transformer

\( R_L \) transmission line equivalent resistance per phase

\( R_{1d} \) \( d \)-axis amortisseur winding resistance

\( R_{1q} \) \( q \)-axis first amortisseur winding resistance

\( R_{2q} \) \( q \)-axis second amortisseur winding resistance

\( R_{\text{shunt}} \) shunt resistor of the dynamic braking

\( S_1, S_2 \) load number 1 and 2

\( t \) time

\( t_{c} - t_r \) a fault of duration of \( t_c \) cycles followed by a successful reclosing after \( t_r \) cycles (\( t_r \) is measured from the instant of fault clearing)

\( t_{c} - t_r - t_{c1} \) a fault of duration of \( t_c \) cycles followed by an unsuccessful reclosing after \( t_r \) cycles and a subsequent clearing after \( t_{c1} \) cycles

\( t_r \) reclosing time

\( T_D \) damping torque coefficient

TCSC Thyristor Controlled Series Capacitor

TCSC1, TCSC2 TCSC bank number 1 and 2

\( T_E \) electromagnetic torque

\( T_{E_k} \) electromagnetic torque of generator \( G_k \), where \( k = 1, 2, 3 \)

\( T_M \) mechanical torque in per unit

\( T_S \) synchronizing torque coefficient

\( u(t) \) control signal of the dynamic braking

\( v_a, v_b, v_c \) instantaneous generator terminal voltage

xviii
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{ab}, V_{bb}, V_{ck}$</td>
<td>instantaneous generator terminal voltage of generator $G_k$, where $k = 1, 2, 3$</td>
</tr>
<tr>
<td>$V$</td>
<td>RMS phase-to-ground voltage of transmission line</td>
</tr>
<tr>
<td>$V_A, V_B, V_C$</td>
<td>RMS transmission line voltages of phases A, B, C</td>
</tr>
<tr>
<td>$V_C$</td>
<td>capacitor voltage</td>
</tr>
<tr>
<td>$V_T$</td>
<td>thyristor voltage</td>
</tr>
<tr>
<td>$V_I$</td>
<td>RMS induced phase-to-ground voltage of isolated transmission line</td>
</tr>
<tr>
<td>$\dot{X}$</td>
<td>first derivative of $X$</td>
</tr>
<tr>
<td>$X$</td>
<td>state variable</td>
</tr>
<tr>
<td>$X_B$</td>
<td>additional capacitive reactance</td>
</tr>
<tr>
<td>$X_C$</td>
<td>nominal reactance of TCSC</td>
</tr>
<tr>
<td>$X-I$</td>
<td>reactance versus line current of TCSC</td>
</tr>
<tr>
<td>$X_G$</td>
<td>generator internal reactance</td>
</tr>
<tr>
<td>$X_L$</td>
<td>transmission line reactance</td>
</tr>
<tr>
<td>$X_M$</td>
<td>motor internal reactance</td>
</tr>
<tr>
<td>$X_{net}$</td>
<td>net reactance of TCSC</td>
</tr>
<tr>
<td>$X_S$</td>
<td>small reactance in series with thyristor</td>
</tr>
<tr>
<td>$X_T$</td>
<td>total reactance of $X_L, X_M$ and $X_G$</td>
</tr>
<tr>
<td>$X_0$</td>
<td>initial condition of $X$</td>
</tr>
<tr>
<td>$Z_L$</td>
<td>transmission line series impedance per phase</td>
</tr>
<tr>
<td>$\delta$</td>
<td>angular position of the rotor with respect to a synchronous rotating reference.</td>
</tr>
<tr>
<td>$\delta_G$</td>
<td>generator internal angle</td>
</tr>
<tr>
<td>$\delta_L$</td>
<td>angular difference between the terminal voltages of the generator and motor</td>
</tr>
<tr>
<td>$\delta_M$</td>
<td>motor internal angle</td>
</tr>
<tr>
<td>$\delta_o$</td>
<td>initial value of rotor angle.</td>
</tr>
<tr>
<td>$\delta_{ik}$</td>
<td>generator $G_k$ load angle measured with respect to generator $G_1$ load angle, where $k = 2, 3$</td>
</tr>
<tr>
<td>$\omega_k$</td>
<td>rotor angular velocity of generator $G_k$, where $k = 1, 2, 3$</td>
</tr>
</tbody>
</table>
\( \omega_r \)  
rotor angular velocity

\( \omega_0 \)  
rated angular velocity of rotor

\( \psi \)  
instantaneous value of flux linkage

\( \psi_a, \psi_b, \psi_c \)  
three-phase armature flux linkage

\( \psi_d \)  
d-axis stator flux linkage

\( \psi_{fd} \)  
field circuit flux linkage

\( \psi_q \)  
q-axis stator flux linkage

\( \psi_0 \)  
0-sequence stator flux linkage

\( \psi_{1d} \)  
d-axis amortisseur circuit flux linkage

\( \psi_{1q} \)  
q-axis first amortisseur circuit flux linkage

\( \psi_{2q} \)  
q-axis second amortisseur circuit flux linkage

\( \theta \)  
angle by which d-axis leads the magnetic axis of phase a winding

\( 1d \)  
d-axis amortisseur circuit

\( 1q \)  
q-axis first amortisseur circuit

\( 2q \)  
q-axis second amortisseur circuit
1. INTRODUCTION

1.1 Power System Stability: Basic Concepts and Definitions

*Power system stability* may be broadly defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [1].

Instability in a power system may be manifested in many different ways depending on the system configuration and operating mode. Traditionally, the stability problem has been one of maintaining synchronous operation. Since power systems rely on synchronous machines for generation of electrical power, a necessary condition for satisfactory system operation is that all synchronous machines remain in synchronism or, colloquially, "in step." This aspect of stability is influenced by the dynamics of generator rotor angles and power-angle relationships [2].

Instability may also be encountered without loss of synchronism. For example, a system consisting of a synchronous generator feeding an induction motor load through a transmission line can become unstable because of the collapse of load voltage. Maintenance of synchronism is not an issue in this instance; instead, the concern is stability and control of voltage (voltage stability) [3,4]. This form of instability can also occur in loads covering an extensive area supplied by a large system.

In the evaluation of stability, the concern is the behaviour of the power system when subjected to a transient *disturbance*. The disturbance may be small or large. Small disturbances in the form of load changes take place continually, and the system adjusts itself to the changing conditions. The system must be able to operate satisfactorily under these conditions and successfully supply the maximum amount of load. It must also be capable of surviving numerous disturbances of a severe nature, such as a short-circuit on a transmission line, loss of a large generator or load, or loss of...
a tie between two subsystems. The system response to a disturbance involves much of the equipment. For example, a short-circuit on a critical element followed by its isolation by protective relays will cause variations in power transfers, machine rotor speeds, and bus voltages; the voltage variations will actuate both generator and transmission system voltage regulators; the speed variations will actuate prime mover governors; the change in tie line loadings may actuate generation controls; the changes in voltage and frequency will affect loads on the system in varying degrees depending on their individual characteristics. In addition, devices used to protect individual equipment may respond to variations in system variables and thus affect the system performance. In any given situation, however, the responses of only a limited number of equipment may be significant. Therefore, many assumptions are usually made to simplify the problem and to focus on factors influencing the specific type of stability problem. The understanding of stability problems is greatly facilitated by the classification of stability into two categories, namely rotor stability and voltage stability. The latter form of stability is out of the scope of this thesis.

1.1.1 Rotor Angle Stability

*Rotor angle stability* is the ability of interconnected synchronous machines of a power system to remain in synchronism. The stability problem involves the study of the electromechanical oscillations inherent in power systems. A fundamental factor in this problem is the manner in which the power outputs of synchronous machines vary as their rotors oscillate. A brief discussion of synchronous machine characteristics is helpful as a first step in developing the related basic concepts.

1.1.1.1 Synchronous Machine Characteristics [5,6]

A synchronous machine has two essential elements: the field and the armature. Normally, the field is on the rotor and the armature is on the stator. The field winding is excited by direct current. When the rotor is driven by a prime mover (turbine), the rotating magnetic field of the field winding induces alternating voltages in the three-phase armature windings of the stator. The frequency of the induced alternating voltages and of the resulting currents that flow in the stator windings when a load is
connected depends on the speed of the rotor. The frequency of the stator electrical quantities is thus synchronized with the rotor mechanical speed; hence the designation "synchronous machine."

When two or more synchronous machines are interconnected, the stator voltages and currents of all the machines must have the same frequency and the rotor mechanical speed of each is synchronized to this frequency. Therefore, the rotors of all interconnected synchronous machines must be in synchronism.

The physical arrangement (spatial distribution) of the stator armature windings is such that the time-varying alternating currents flowing in the three-phase windings produce a rotating magnetic field that, under steady-state operation, rotates at the same speed as the rotor. The stator and rotor fields react with each other and an electromagnetic torque results from the tendency of the two fields to align themselves. In a generator, this electromagnetic torque opposes rotation of the rotor, so that mechanical torque must be applied by the prime mover to sustain rotation. The electrical torque (or power) output of the generator is changed only by changing the mechanical torque input by the prime mover. The effect of increasing the mechanical torque input is to advance the rotor to a new position relative to the revolving magnetic field of the stator. Conversely, a reduction of mechanical torque or power input will retard the rotor position. Under steady-state operating conditions, the rotor field and the revolving field of the stator have the same speed. However, there is an angular separation between them depending on the electrical torque (or power) output of the generator.

In the above discussion, the terms torque and power have been used interchangeably. This is common practice in the power system stability literature, since the average rotational velocity of the machines is constant even though there may be small momentary excursions above and below synchronous speed. The per unit values of torque and power are, in fact, almost equal.

1.1.1.2 Power versus angle relationship

An important characteristic that has a bearing on power system stability is the relationship between interchange power and angular positions of the rotors of
synchronous machines. This relationship is highly nonlinear. To illustrate this, consider the simple system shown in Figure 1.1(a). It consists of two synchronous machines connected by a transmission line having an inductive reactance $X_L$ and negligible resistance and capacitance. Assume that machine 1 represents a generator feeding power to a synchronous motor represented by machine 2.

The power transferred from the generator to the motor is a function of angular separation $\delta$ between the rotors of the two machines. This angular separation is due to three components: generator internal angle $\delta_G$ (angle by which the generator rotor leads the revolving field of the stator); angular difference between the terminal voltages of the generator and motor (angle by which the stator field of the generator leads that of the motor); and the internal angle of the motor (angle by which the rotor lags the revolving stator field). Figure 1.1(b) shows a model of the system that can be used to determine the power versus angle relationship. A simple model comprising an internal voltage behind an effective reactance is used to represent each synchronous machine. The value of the machine reactance used depends on the purpose of the study. For analysis of steady-state performance, it is appropriate to use the synchronous reactance with the internal voltage equal to the excitation voltage.

A phasor diagram identifying the relationships between generator and motor voltages is shown in Figure 1.1(c). The power transferred from the generator to the motor is given by [5]:

$$ P = \frac{|E_G||E_M|}{|X_T|} \sin \delta \quad (1.1) $$

where

$$ X_T = X_G + X_L + X_M. $$

The corresponding power versus angle relationship is plotted in Figure 1.1(d). With the somewhat idealized models used for representing the synchronous machines, the power varies as a sine of the angle: a highly nonlinear relationship. With more accurate machine models including the effects of automatic voltage regulators, the variation in power with angle would deviate significantly from the sinusoidal relationship; however, the general form would be similar. When the angle is zero,
Figure 1.1: Power transfer characteristic of a two-machine system: (a) single-line diagram, (b) idealized model, (c) phasor diagram, (d) power-angle curve.
no power is transferred. As the angle is increased, the power transfer increases up to a maximum. After a certain angle, nominally 90°, a further increase in angle results in a decrease in power transferred. There is thus a maximum steady-state power that can be transmitted between the two machines. The magnitude of the maximum power is directly proportional to the machine internal voltages and inversely proportional to the reactance between the voltages, which includes reactance of the transmission line connecting the machines and the reactances of the machines.

When there are more than two machines, their relative angular displacements affect the interchange of power in a similar manner. However, limiting values of power transfers and angular separation are a complex function of generation and load distribution. An angular separation of 90° between any two machines (the nominal limiting value for a two-machine system) in itself has no particular significance.

1.1.2 The Stability Phenomena

Stability is a condition of equilibrium between opposing forces. The mechanism by which interconnected synchronous machines maintain synchronism with one another is through restoring forces, which act whenever there are forces tending to accelerate or decelerate one or more machines with respect to other machines. Under steady-state conditions, there is equilibrium between the input mechanical torque and the output electrical torque of each machine, and the speed remains constant. If the system is perturbed this equilibrium is upset, resulting in acceleration or deceleration of the rotors of the machines according to the laws of motion of a rotating body. If one generator temporarily runs faster than another, the angular position of its rotor relative to that of the slower machine will advance. The resulting angular difference transfers part of the load from the slow machine to the fast machine, depending on the power-angle relationship. This tends to reduce the speed difference and hence the angular separation. The power-angle relationship, as discussed above, is highly nonlinear. Beyond a certain limit, an increase in angular separation is accompanied by a decrease in power transfer; this increases the angular separation further and leads to instability. For any given situation, the stability of the system depends on whether or not the deviations in angular positions of the rotors result in sufficient restoring torques.
When a synchronous machine loses synchronism or "falls out of step" with the rest of the system, its rotor runs at a higher or lower speed than that required to generate voltages at system frequency. The "slip" between rotating stator field (corresponding to system frequency) and the rotor field results in large fluctuations in the machine power output, current, and voltage; this causes the protection system to isolate the unstable machine from the system.

Loss of synchronism can occur between one machine and the rest of the system or between groups of machines. In the latter case synchronism may be maintained within each group after its separation from the others.

With electric power systems, the change in electrical torque of a synchronous machine following a perturbation can be resolved into two components [7]:

$$\Delta T_e = T_s \Delta \delta + T_D \Delta \omega$$

\(\Delta T_e\) is the component of torque change in phase with the rotor angle perturbation \(\Delta \delta\) and is referred to as the synchronizing torque component; \(T_s\) is the synchronizing torque coefficient.

\(T_D\Delta \delta\) is the component of torque in phase with the speed deviation \(\Delta \omega\) and is referred to as the damping torque component; \(T_D\) is the damping torque coefficient.

System stability depends on the existence of both components of torque for each of the synchronous machines. Lack of sufficient synchronizing torque results in instability through an aperiodic drift in rotor angle. On the other hand, lack of sufficient damping torque results in oscillatory instability as shown in Figure 1.2 [8].

For convenience in analysis and for gaining useful insight into the nature of stability problems, it is usual to characterize the rotor angle stability phenomena in terms of the following two categories [1,8-10]:

(a) Small-signal (or small-disturbance) stability is the ability of the power system to maintain synchronism under small disturbances. Such disturbances occur continually on the system because of small variations in loads and generation.
Figure 1.2: Types of rotor angle instabilities: (a) aperiodic, (b) oscillatory.

conditions. In applying these methods to the solution of specific stability problems, it is important to keep in mind the overall performance of the power system.
Many of the methods for stability enhancement described in this section are options normally available for economic design of the system. With proper design and application they should greatly contribute to the flexibility of system operation without compromising other aspects of system performance. Some of the methods described here can, however, impose duty on some of the equipment. Their application, therefore, has to be based on a careful assessment of the benefits and costs.

Methods of improving transient stability try to achieve one or more of the following effects:

(a) Reduction in the disturbing influence by minimizing the fault severity and duration.

(b) Increase of the restoring synchronizing forces.

(c) Reduction of the accelerating torque through control of prime-mover mechanical power.

(d) Reduction of the accelerating torque by applying artificial load. The following are various methods of achieving these objectives.

1.2.1 High-Speed Fault Clearing

The amount of kinetic energy gained by the generators during a fault is directly proportional to the fault duration; the quicker the fault is cleared, the less disturbance it causes. Two-cycle breakers, together with high-speed relays and communication, are now widely used in locations where rapid fault clearing is important [11].

In special circumstances, even faster clearing may be desirable. Combined with a rapid response overcurrent type sensor, which anticipates fault magnitude, nearly one-cycle total fault duration is attained [12]. One-cycle breakers are not yet in widespread use.

1.2.2 Reduction of Transmission System Reactance

The series inductive reactances of transmission networks are primary determinants of stability limits. The reduction of the transmission network reactances improves transient stability by increasing postfault synchronizing power transfers. Obviously, the most direct way of achieving this is by reducing the reactances of transmission circuits,
which are determined by the voltage rating, line and conductor configurations, and number of parallel circuits. The following are additional methods of reducing the network reactances:

(a) Use of transformers with lower leakage reactances.
(b) Series capacitor compensation of transmission lines [13,14].

Typically, the per unit transformer leakage reactance ranges are between 0.1 and 0.15. For newer transformers, the minimum acceptable leakage reactance that can be achieved within the normal transformer design practices has to be established in consultation with the manufacturer. In many situations, there may be a significant economic advantage in opting for a transformer with the lowest possible reactance.

Series capacitors directly offset the line series reactance. The maximum power transfer capability of a transmission line may be significantly increased by the use of series capacitor banks. This directly translates into enhancement of transient stability, depending on the facilities provided for bypassing the capacitor during faults and for reinsertion after fault clearing. Speed of reinsertion is an important factor in maintaining transient stability. Early designs of protective gaps and bypass switches limited the benefits achievable by series capacitor compensation. However, with the present trend of using nonlinear resistors of zinc oxide, the reinsertion is practically instantaneous.

It is important to mention one problem with series capacitor compensation, which is the possibility of subsynchronous resonance with the nearby turbo alternators. This aspect must be analyzed carefully and appropriate preventative measures must be taken [15,16].

Traditionally, series capacitors have been used to compensate for very long overhead lines. Recently, there has been an increasing recognition of the advantages of compensating shorter, but heavily loaded, lines by using series capacitors.

For transient stability applications, the use of switched series capacitors offers some advantages [14]. Upon detection of a fault or power swing, a series capacitor bank can be switched in and then removed about 0.5 second later. Such a switched bank can be located in a substation where it can serve several lines.

For a given transient stability limit, the aggregate rating of series capacitors required is less if some are switched than if all are unswitched. The scheme with a
portion of the capacitors switched reduces the angular swings of the machines, and this in turn reduces fluctuation of loads, particularly those near the electrical center.

Protective relaying is made more complex when series compensation is used, particularly if the series capacitors are switched.

1.2.3 Regulated Shunt Compensation

Shunt compensation capable of maintaining voltages at selected points of the transmission system can improve system stability by increasing the flow of synchronizing power among interconnected generators. Synchronous condensers or static var compensators can be used for this purpose [17,18].

Regulated shunt compensation increases the maximum power transfer capability of a long transmission line. This clearly enhances transient stability.

1.2.4 Dynamic Braking

Dynamic braking uses the concept of applying an artificial electrical load during a transient disturbance to increase the electrical power output of generators and thereby reduce rotor acceleration [19].

One form of dynamic braking involves the switching in of controlled shunt resistors banks for about 0.5 second following clearing of a fault to reduce the accelerating power of nearby generators and remove the kinetic energy gained during the fault. The damping provided by the braking resistors may be improved if their switching circuits are equipped with a bang-bang controller implementing the strategy defined by the following equation [20]:

\[ R(t) = \begin{cases} R_{\text{shunt}} & \Delta \omega > 0 \\ 0 & \Delta \omega < 0 \end{cases} \]  

(1.3)

where \( \Delta \omega \) is the deviation of the generator speed.

To date, braking resistors have been applied only to hydraulic generating stations remote from load centers. Hydraulic units, in comparison to thermal units, are quite rugged; therefore, they can withstand the sudden shock from the switching in of resistors without any adverse effect on the units.
If braking resistors are applied to thermal units, the effect on shaft fatigue life must be carefully examined. If the switching duty is found unacceptable, the switching in of the resistors may have to be performed in three or four steps spread over one full cycle of the lowest torsional mode.

The braking resistors used to date are all shunt devices. Alternatively, *series resistors* may be used to provide the braking effect. In this case, the energy dissipated is proportional to the generator current rather than to the voltage. One way of inserting the resistors in series is to install a star-connected three-phase resistor arrangement with a bypass switch in the neutral of the generator step-up transformer to reduce resistor insulation and switch requirements. The resistor is inserted during a transient disturbance by opening the bypass switch.

Another form of braking resistor application that enhances system stability for unbalanced ground faults only, consists of a resistor connected permanently between the ground and the neutral of the Y-connected high-voltage winding of the generator step-up transformer, as shown in Figure 1.4. Under balanced conditions no current flows through the neutral resistor. When line-to-ground or double line-to-ground faults occur, current flows through the neutral connection and the resistive losses act as a dynamic brake.

### 1.2.5 Reactor Switching

Shunt reactors near generators provide a simple and convenient means of improving transient stability. The reactor normally remains connected to the network.
Figure 1.4: Braking resistors for unbalanced ground faults.

The resulting reactive load increases the generator internal voltage, and this is beneficial to stability. Following a fault, switching out the reactor further improves stability.

1.2.6 Independent-Pole Operation of Circuit Breakers

Independent-pole operation refers to the use of separate mechanisms for each phase of the circuit-breaker so that the three phases are closed and opened independently of each other [21]. As a result, the failure of one pole will not restrict the operation of the other two poles. Although the breaker poles operate independently of each other, the relaying system is normally arranged to trip all three poles for any type of fault.

Independent-pole operation can be used advantageously at locations where the system design criteria include a three-phase fault compounded by breaker failure. Maintaining system stability for the contingency of a three-phase fault with all three poles of a primary circuit-breaker failing to open is extremely difficult. With breakers designed for independent-pole operation, a failure of all three poles is highly improbable. The use of duplicate relay systems, circuit-breaker trip coils, and operating mechanisms practically guarantees that at least two poles will open. Therefore, the independent operation of the failed breaker will reduce a three-phase fault to a single line-to-ground fault when two of the poles open. Thus, the severity of a three-phase fault with a stuck breaker is significantly reduced.

1.2.7 Single-Pole Switching

Single-pole switching uses separate operating mechanisms on each phase; for
single line-to-ground faults, the relaying is designed to trip only the faulted phase, followed by fast reclosure within 0.5 to 1.5 seconds [22]. For multiphase faults, all three phases are tripped.

During the period when one phase is open, power is transferred over the remaining two phases.

As most faults on transmission lines are of the single line-to-ground type, opening and reclosing of only the faulted phase results in an improvement in transient stability over three-phase tripping and reclosing.

Single-pole switching is particularly attractive for situations where a single major line connects two systems or where a single major line connects a generating station to the rest of the system. It may also be used on systems with multiple lines to improve system security against multiple contingency disturbances.

There are three potential problems that need to be considered in applying single-pole switching:

- Secondary-arc extinction.
- Fatigue duty on turbine-generator shafts and turbine blades.
- Thermal duty on nearby generators due to negative-sequence currents.

1.2.8 Steam Turbine Fast-Valving

Fast valving (or early valving, as it is sometimes referred to) is a technique applicable to thermal units to assist in maintaining power system transient stability [23]. It involves rapid closing and opening of steam valves in a prescribed manner to reduce the generator accelerating power following the recognition of a severe transmission system fault.

1.2.9 Generator Tripping

The selective tripping of generating units for severe transmission system contingencies has been used as a method of improving system stability for many years [24]. The rejection of generation at an appropriate location in the system reduces power to be transferred over the critical transmission interfaces. Since generating units can be tripped rapidly, this is a very effective means of improving transient stability.
Unless special facilities are provided, the rejected unit goes through a standard shut-down and start-up cycle; consequently, full power may not be available for several hours. A practice used by many utilities is to design thermal units so that, after tripping, they continue to run, supplying unit auxiliaries. This permits the units to be resynchronized to the system and restored to full load in about 15 to 30 minutes [25].

1.2.10 Controlled System Separation and Load Shedding

Controlled separation may be used to prevent a major disturbance in one part of an interconnected system from propagating into the rest of the system and causing a severe system breakup [26]. The initiating disturbance may be the loss of a major transmission line (ac or dc) carrying a large amount of power or loss of a significant amount of generation. The incipient instability in such cases is usually characterized by sudden changes in tie line power. If this is detected in time and the information is used to initiate corrective actions, severe system upsets can be averted.

The impending system instability is detected by monitoring one or more of the following system quantities: sudden change in power flow through specific transmission circuits, change of bus voltage angle, rate of power change, and circuit-breaker auxiliary contacts.

Upon detection of the impending instability, controlled system separation is initiated by opening the appropriate tie lines before cascading outages can occur. In some instances it may be necessary to shed selected loads to balance generation and load in the separated systems.

1.2.11 High-Speed Excitation Systems

Significant improvements in transient stability can be achieved through rapid temporary increase of generator excitation [27,28]. The increase of generator field voltage during a transient disturbance has the effect of increasing the internal voltage of the machine; this in turn increases the synchronizing power.

During a transient disturbance following a transmission system fault and clearing of the fault by isolating the faulted element, the generator terminal voltage is low. The automatic voltage regulator responds to this condition by increasing the generator field
voltage, and this has a beneficial effect on the transient stability. The effectiveness of this type of control depends on the ability of the excitation system to quickly increase the field voltage to the highest possible value. High-initial-response excitation systems with high-ceiling voltages are most effective in this regard. Ceiling voltage are, however, limited by generator rotor insulation considerations. For thermal units, the ceiling voltages are limited to about 2.5 to 3.0 times the rated-load field voltage.

1.3 Objective of the Thesis

The major objective of the research described in this thesis was to search for an economical and practical technique for enhancing power system transient stability during clearing and high-speed reclosing of unsymmetrical faults on double-circuit transmission lines. In this context, the following summarizes the specific objectives of this thesis:

1. To develop a mathematical model for the various components of a typical power system which enables the evaluation of transient stability.
2. To investigate the effect of a proposed technique for improving power system transient stability using Thyristor Controlled Series Capacitor (TCSC).

1.4 Outline of the Thesis

This thesis is organized into six chapters. This chapter presents a general introduction to the power system stability problem including physical concepts, classification, and definition of related terms. Analysis of elementary power system configurations by means of idealized models illustrates some of the fundamental stability properties of power systems.

Chapter 2 introduces the system used for the studies reported in this thesis as well as the mathematical models of its various components. The mathematical formulation of the transient stability problem is also described in this chapter.

Chapter 3 examines the effect of high-speed reclosing of system faults on power system transient stability. Single and selective-pole switching techniques are introduced in this chapter.
Chapter 4 introduces an adaptive short-time compensation and reclosing technique for improving power system stability during clearing and high-speed reclosing of unsymmetrical faults on double-circuit transmission lines. In this context, both the adaptive short-time compensation and adaptive selective-pole reclosing are presented. Since the proposed adaptive short-time compensation technique utilizes a Thyristor Controlled Series Capacitor, a description and modeling of such a component is presented in this chapter.

Chapter 5 demonstrates the effectiveness of the proposed adaptive short-time compensation and reclosing technique in improving the transient stability of the power system. The possibility of boosting the transmission system capacity beyond its nominal value using TCSC is also presented in this chapter.

Chapter 6 summarizes the research work described in this thesis and presents some general conclusions.
2. POWER SYSTEM MODELING FOR TRANSIENT STABILITY STUDIES

2.1 General

It is necessary, as a first step, to give an outline and mathematical representation of the system used in this studies. In this chapter, the system used for the studies reported in this thesis is described and the mathematical models of its various components are presented.

2.2 System Under Study

The system used for investigation in this thesis is shown in Figure 2.1. It consists of three generators, two load buses, three single-circuit and three double-circuit transmission lines. The system data is given in Appendix A.

2.3 Synchronous Machine Model

Figure 2.2 shows the circuit involved in the analysis of a synchronous machine. The stator circuits consist of three-phase armature windings carrying alternating currents. The rotor circuits comprise field and amortisseur windings. The field winding is connected to a source of direct current. For the analysis conducted in this thesis, the currents in the amortisseur (solid rotor and/or damper windings) are assumed to flow in two sets of closed circuits: one set whose flux is in line with that of the field along the $d$-axis and the other set whose flux is right angles to the field axis or along the $q$-axis. Since it is seldom necessary for system stability studies to represent more than two or three rotor circuits in each axis [10], the synchronous machine is represented by two circuits in each axis ($f_d, l_d, l_q, 2q$, Figure 2.2).
Figure 2.1: System under study.
Figure 2.2: Stator and rotor circuits of a synchronous machine.

The per unit equations of the synchronous machine in the \( d-q-0 \) reference frame (Figure 2.3) [29] are as follows:

Per unit stator voltage equations:

\[
e_d = p\psi_d - \psi_d \omega_r - R_a i_d \tag{2.1}
\]

\[
e_q = p\psi_q + \psi_d \omega_r - R_a i_q \tag{2.2}
\]

\[
e_0 = p\psi_0 - R_q i_0 \tag{2.3}
\]

Per unit rotor voltage equations:

\[
e_{fd} = p\psi_{fd} + R_{fd}i_{fd} \tag{2.4}
\]

\[
0 = p\psi_{1d} + R_{1d}i_{1d} \tag{2.5}
\]

\[
0 = p\psi_{1q} + R_{1q}i_{1q} \tag{2.6}
\]

\[
0 = p\psi_{2q} + R_{2q}i_{2q} \tag{2.7}
\]
Figure 2.3: Modeling of the synchronous machine in the $d$-$q$-$0$ reference frame.

Per unit stator flux linkage equations:

\[
\psi_d = -(L_{ad} + L_1) i_d + L_{ad} i_{fd} + L_{ad} i_{1d} \tag{2.8}
\]

\[
\psi_q = -(L_{aq} + L_1) i_q + L_{aq} i_{1q} + L_{aq} i_{2q} \tag{2.9}
\]

\[
\psi_0 = -L_0 i_0 \tag{2.10}
\]

Per unit rotor flux linkage equations:

\[
\psi_{fd} = L_{fd} i_{fd} + L_{f1d} i_{1d} - L_{ad} i_d \tag{2.11}
\]

\[
\psi_{1d} = L_{f1d} i_{fd} + L_{11d} i_d - L_{ad} i_d \tag{2.12}
\]

\[
\psi_{1q} = L_{11d} i_{1q} + L_{aq} i_{2q} - L_{aq} i_q \tag{2.13}
\]

\[
\psi_{2q} = L_{aq} i_{1q} + L_{22q} i_{2q} - L_{aq} i_q \tag{2.14}
\]

Per unit air-gap torque:
The equation of motion is given by

\[
\frac{2H}{\omega_0} \frac{d^2 \delta}{dt^2} = T_M - T_E
\] (2.16)

### 2.4 Transmission Line Model

The transmission line is modeled as a transposed non-coupled parameters line using the series impedance representation. The transmission line voltage drop equations in the direction of current flow (Figure 2.4) are thus given by

\[
\begin{bmatrix}
  v_{aa'} \\
v_{bb'} \\
v_{cc'}
\end{bmatrix} =
\begin{bmatrix}
  R_L + pL_L & 0 & 0 \\
  0 & R_L + pL_L & 0 \\
  0 & 0 & R_L + pL_L
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\] (2.17)

![Figure 2.4: Modeling of transmission line.](image)
2.5 Modeling of the Transformer

The transformer in this study is modeled as an ideal transformer. A three-phase transformer is constructed by using three single-phase transformers connected in Y – Y.

2.6 Modeling of System Loads

The system loads are modeled in this study as constant impedances. The formula, which is used in calculating the load impedances, is given by

\[ Z_{Load} = \frac{|V_{Load}|^2}{P_{Load} - jQ_{Load}} \]  

(2.18)

where

- \( Z_{Load} \) = load impedance.
- \( V_{Load} \) = load voltage.
- \( P_{Load} \) = load real power.
- \( Q_{Load} \) = load reactive power.

2.7 Modeling of the Fault Clearing Process

The actual physical breaker operation is considered in the simulation. When a breaker opens to clear a three-phase fault, the phase in which the current passes through zero (point X, Figure 2.5(a)) is interrupted first with the remaining phases (B and C, Figure 2.5(a)) left in a new fault configuration (line-to-line fault). The interruption of the current in the first phase forces the currents in the two remaining phases immediately to become equal and opposite. Complete clearance will take place by the simultaneous interruption of these two phases when their currents pass through zero (point Y, Figure 2.5(a)).

On the other hand, in the case of clearing a three-phase-to-ground fault, the phase in which the current first passes through zero (point X, Figure 2.5(b)) is interrupted first with the remaining phases (C and B, Figure 2.5(b)) left in a new fault configuration.
Figure 2.5: Fault clearing process modeling: (a) three-phase fault, (b) three-phase-to-ground fault.
(double line-to-ground fault). Such a fault configuration will be cleared by the sequential interruption of these two phases when their currents pass through zero (points Y and Z, Figure 2.5(b)).

2.8 Mathematical Formulation of the Transient Stability Problem

The dynamic model for an interconnected power-system can be completely described by a set of highly nonlinear differential equations:

\[ \dot{X} = f(X, V) \]  

subject to the initial conditions:

\[ X(0) = X_0 \]

and a set of nonlinear algebraic equations

\[ 0 = g(X, V) \]

where \( X \) are the state variables of the differential equations, also known as generator variables, which describe the dynamics of the system. The generator variables typically include rotor angle, velocity deviation, mechanical power etc. Further, \( V \) are the network variables, for instance currents in the loads and generators.

This set of differential equations can be solved using explicit or implicit integration methods. Implicit integration methods have the advantage of providing better numerical stability and being able to avoid the difficulty of stiff problems [30-31]. For these reasons in power system application they are preferred over their explicit counterparts. In the studies conducted in this thesis, the Electromagnetic Transient Program (EMTP) (Appendix B) [32] is used for modeling the various system components and producing the time simulation results.
3. IMPACT OF HIGH-SPEED RECLOSING ON POWER SYSTEM TRANSIENT STABILITY

3.1 Introduction

In this chapter, studies are carried out to explore the effect of high-speed reclosing of system faults on power system transient stability. A comparative study between the effect of triple- and single-pole reclosing of single line-to-ground faults on power system transient stability is also presented in this chapter. In all the investigations conducted in this chapter, and hereafter, faults are assumed to occur on the transmission lines of the study system shown in Figure 3.1, and to be cleared by circuit breaker operations at both ends of the lines.

3.2 Transmission Line Reclosing Practices

Since operating experience has demonstrated that over 80% of transmission line faults are of temporary nature, it has become common practice to automatically reclose the circuit breakers of a line tripped out due to a fault [33]. If the fault persists, the circuit breakers are tripped a second time, usually with no further attempts to reclose them again automatically (single-shot reclosing). However, in a few cases, a second automatic delayed reclosure may be attempted (multiple-shot reclosing).

There are a number of forms of reclosing practice, ranging from the fastest possible automatic reclosing at both ends of the line to the manual operation of the breakers with synchrocheck supervision. The most widely used reclosing methods are [34]:

1. Unrestricted High-Speed Reclosing: This refers to the practice of reclosing the transmission line circuit breakers at both ends of the line as rapidly as possible following a fault trip out, regardless of the fault type. Successful reclosing in this case cannot occur until the fault arc has extinguished and the dielectric
Figure 3.1: Fault locations on the system under study.
strength has recovered. This may require more than half a second for EHV transmission lines.

2. Delayed Reclosing: This refers to automatic reclosing of the transmission line circuit breakers with an additional time delay beyond the minimum required for arc extinguishing and dielectric recovery. This additional time delay usually varies from one to sixty seconds. The main reason for this time delay is to reduce the probability of reclosing back into a fault (unsuccessful reclosure).

3. Synchrocheck Delayed Reclosing: This refers to the practice of reclosing the line first from the end which is remote from the generating station, with the breakers at the generator end being reclosed only after check relays (usually voltage monitor and phase angle) indicate that the fault no longer exists. Several second time delay is inherent in this type of reclosing. Synchrocheck delayed reclosing would be of a little value in strong networks where the remote line terminal is electrically close to the generating station through other connections, or if another generating station is located close to the remote end of the line.

4. Selective Reclosing: This refers to the practice of distinguishing the type of fault and permitting high-speed reclosing only for single line-to-ground and line-to-line faults. Selective reclosing might also be applied on some other basis, such as the distance of the fault from the generating plant, to screen out the more severe close-in faults.

A principal advantage of high-speed reclosing is that it restores system integrity as quickly as possible following a temporary fault. A rapid restoration of the system to its prefault conditions minimizes the probability of multiple contingencies and reestablishes the margins upon which the system integrity is based [35].

The practice of high-speed reclosing is beneficial on transmission lines near generating units. This is becoming increasingly true in EHV systems since, in this case, the inherently greater line capabilities together with economic and land use consideration tend to limit the number of transmission outlets from the generating
stations. In these situations, high-speed reclosing helps to reduce the probability of a unit or plant being lost due to instability or trapped during lightning, wind or sleet storms [35].

3.3 Impact of High-Speed Reclosing on Power System Transient Stability

Figure 3.2 displays typical time responses showing the generator electromagnetic torques, stator currents and voltages, rotor currents, speeds, and load angles during a 4-cycle three-phase fault on line L_2 at F_1. The fault results in a reduction in the voltages at the system buses (drops to zero at bus 1) and the generators are no longer able to deliver their rated power to the system. This imbalance between the mechanical and electromagnetic torques causes the generators to accelerate and the rotor angles to increase. At the instant of clearing the fault by opening CB_1 and CB_2, the sudden change in the network voltages at the increased generator load angles is equivalent to faulty synchronizations. The result is sudden pulsating electromagnetic torques. As it can be seen from Figure 3.2, the generator load angles measured with respect to the load angle of generator G_1 are reaching new equilibrium state, and the system is stable.

Figure 3.3 and 3.4 demonstrate the effect of high-speed reclosing of the three-phase fault of Figure 3.2 on the transient stability of the system. Thirty cycles after fault clearing, line L_2 is reclosed successfully (the fault no longer exists) by closing CB_1 and CB_2. This results also in pulsating electromagnetic torques as shown in Figure 3.3. Moreover, as the result of the reclosing, the system is restored to its prefault conditions and the generators are able to deliver their rated power to the system. Hence, they decelerate and their rotor angles oscillate around their prefault values. As it can be seen from Figure 3.4, high-speed reclosing results in an improvement in the system stability by reducing the maximum second swing of the generator load angles as well as reducing the generator speeds.

3.4 Single-Pole Reclosing

When a single line-to-ground fault occurs on a transmission line, the general protection practice of many utilities is to interrupt all the three-phases of the faulted line [36]. If the fault is temporary in nature, such as for a lightning strike, the tripped line
Figure 3.2: Generator electromagnetic torques, stator currents and voltages, rotor currents, speeds and load angles during a 4-cycle three-phase fault at F₁.
Figure 3.2 (contd.): Generator electromagnetic torques, stator currents and voltages, rotor currents, speeds and load angles during a 4-cycle three-phase fault at F₁.
Figure 3.2 (contd.): Generator electromagnetic torques, stator currents and voltages, rotor currents, speeds and load angles during a 4-cycle three-phase fault at F₁.
Figure 3.2 (contd.): Generator electromagnetic torques, stator currents and voltages, rotor currents, speeds and load angles during a 4-cycle three-phase fault at F₁.
Figure 3.2 (contd.): Generator electromagnetic torques, stator currents and voltages, rotor currents, speeds and load angles during a 4-cycle three-phase fault at F₁.
Figure 3.3: Generator electromagnetic torques during successful reclosing of a 4-30 cycle three-phase fault at F₁.
Figure 3.4: Generator speeds and load angles during a 4-cycle three-phase fault at $F_1$ (— without reclosing, --- with a 30-cycle successful reclosing).
Figure 3.4 (contd.): Generator speeds and load angles during a 4-cycle three-phase fault at F₁ (— without reclosing, - - - with a 30-cycle successful reclosing).
would be reclosed successfully. Such sequence of switching operations is commonly referred to as triple-pole reclosing (Figure 3.5(a))[37]. An alternative approach of reclosing which involves tripping and reclosing only the circuit breakers of the faulted phase is known as single-pole reclosing (Figure 3.5(b)). However, in the case of unsuccessful single-pole reclosing, triple-pole switching is used to interrupt the three-phases of the faulted line.

A primary benefit of the use of single-pole reclosing is improvement of the system reliability for unpredictable, multiple-contingency conditions. Single-pole reclosing if successful represents a significant step in improving the system stability and performance since the majority of faults on EHV transmission lines are single line-to-ground and of temporary nature [38].

3.4.1 Impact of Single-Pole Reclosing on Power System Transient Stability

Figure 3.6 shows the generator electromagnetic torques, speeds and load angles during successful triple-pole reclosing of a 4-45 single cycle line-to-ground fault (phase A) on line L₁ at F₂. As it can be seen from Figure 3.1, line L₁ connects the generator buses, bus 1 and bus 2. A fault on this line followed by a triple-pole switching results in a significant increase in the generator load angles as shown in Figure 3.6 since no power is transferred between buses 1 and 2. The figure shows also that after reclosing, the system is stable and the transient stability is improved.

Figure 3.7 shows the generator electromagnetic torques and the rotor currents of generator G₁ during a successful 4-45 cycle single-pole reclosing of the same fault of Figure 3.6. The system imbalance during the dead time between fault clearing and reclosing is clearly noticeable in Figure 3.7 as a double frequency (120 Hz) component in the generator electromagnetic torques and the rotor currents. It can be seen also from Figures 3.6 and 3.7 that, at the instant of reclosing, the transients in the generator electromagnetic torques are less in the case of single-pole reclosing than in the case of triple-pole reclosing.

Regarding the system stability, Figure 3.8 shows the generator speeds and load angles for the two reclosing cases of Figures 3.6 (triple-pole) and 3.7 (single-pole). In the case of single-pole switching, some power is transferred during the dead time
Figure 3.5: High-speed reclosing of a single line-to-ground fault: (i) fault; (ii) isolation of the fault; (iii) successful reclosure; (iv) unsuccessful reclosure, (a) triple-pole reclosing, (b) single-pole reclosing.)
Figure 3.6: Generator electromagnetic torques, speeds and load angles during successful triple-pole reclosing of a 4-45 cycle single line-to-ground fault at $F_2$. 
Figure 3.6 (contd.): Generator electromagnetic torques, speeds and load angles during successful triple-pole reclosing of a 4-45 cycle single line-to-ground fault at F₂.
Figure 3.6 (contd.): Generator electromagnetic torques, speeds and load angles during successful triple-pole reclosing of a 4-45 cycle single line-to-ground fault at F₂.
Figure 3.7: Generator electromagnetic torques and rotor currents during successful single-pole reclosing of a 4-45 cycle single line-to-ground fault at F2.
Figure 3.7 (contd.): Generator electromagnetic torques and rotor currents during successful single-pole reclosing of a 4-45 cycle single line-to-ground fault at F2.
Figure 3.8: Generator speeds and load angles during successful reclosing of a 4-45 cycle single line-to-ground fault at F2 (— triple-pole switching, ---- single-pole switching).
Figure 3.8 (contd.): Generator speeds and load angles during successful reclosing of a 4-45 cycle single line-to-ground fault at $F_2$ (—— triple-pole switching, --- single-pole switching).
between buses 1 and 2 through the uninterrupted phases (phases B and C). As it can be seen from Figure 3.8, the accelerations of the generators are less in this case and an improvement in the system transient stability is achieved through a significant reduction in the maximum swing of the generator load angles.

3.5 Selective-Pole Switching

Similar to single-pole switching of single line-to-ground faults, clearing other unsymmetrical faults, namely line-to-line and double line-to-ground faults can also be performed by interrupting only the two faulted phases as illustrated in Figure 3.9.

This technique combined with single-pole switching is called “selective-pole switching”. The primary advantage of selective-pole switching is that it allows some power to be transferred through the unfaulted phase(s) and, therefore, improves the system stability.

3.5.1 Impact of Selective-Pole Switching on Power System Transient Stability

The generator electromagnetic torques during successful reclosing of a 4-45 cycle line-to-line fault on line L1 at F2 are illustrated in Figure 3.10(a) for the case of triple-pole reclosing and in Figure 3.10(b) for the case of selective-pole reclosing. As it can be seen from Figure 3.10, selective-pole switching introduces a double frequency (120 Hz) component in the generator electromagnetic torques during the dead time between fault clearing and reclosing.

Figure 3.11 illustrates the generator speeds and load angles for the two reclosing cases of Figure 3.10. As it can be seen from this figure, the accelerations of the generators are less in the case of selective-pole reclosing and a significant improvement in the system transient stability is achieved through reductions in the maximum swing of the generator load angles.

3.5.1.1 A Special Case of Selective-Pole Switching of Line-to-Line Faults

Due to the nature of the line-to-line fault, clearing such a fault can be done by interrupting only one of the faulted phases as shown in Figure 3.12. From the stability point of view, this switching technique allows more power to be transferred during the
Figure 3.9: Selective pole switching of line-to-line and double line-to-ground faults: (i) fault; (ii) isolation of the fault; (iii) successful reclosure; (iv) unsuccessful reclosure, (a) line-to-line fault, (b) double line-to-ground fault.
Figure 3.10: Generator electromagnetic torques during successful reclosing of a 4-45 cycle line-to-line fault at F2: (a) triple-pole reclosing, (b) selective-pole reclosing.
Figure 3.11: Generator speeds and load angles during successful reclosing of a 4-45 cycle line-to-line fault at F2 (—— triple-pole reclosing, －－－－ selective-pole reclosing).
Figure 3.11 (contd.): Generator speeds and load angles during successful reclosing of a 4-45 cycle line-to-line fault at $F_2$ (— triple-pole reclosing, - - - selective-pole reclosing).
dead time through the two healthy phases than in the case of switching off both of the faulted phases and, therefore, further improves the system stability. This is clearly demonstrated in Figure 3.13 which illustrates the generator speeds and load angles during successful reclosing of a 4-45 cycle line-to-line fault on line L2 at F1 for triple-pole reclosing, selective-pole reclosing (phases A&B) and selective-pole reclosing (phase B). It is worth noting here that this reclosing technique of line-to-line faults is practical and has been performed by some utilities [35].

3.6 Summary

In this chapter, studies were conducted on the study system to investigate the effect of high-speed reclosing of transmission line faults on the transient stability of the power system. The concept of selective-pole switching has also been introduced in this chapter. The results of these studies have shown the benefit of using high-speed
Figure 3.13: Generator speeds and load angles during successful reclosing of a 4-45 cycle line-to-line fault at F_1.
Figure 3.13 (contd.): Generator speeds and load angles during successful reclosing of a 4-45 cycle line-to-line fault at $F_1$. 
reclosing for improving power system stability. Moreover, the significant effect of using selective-pole switching for clearing unsymmetrical faults in enhancing the power system stability in comparison to triple-pole switching of the same faults has been shown.
4. ADAPTIVE SHORT TIME COMPENSATION AND RECLOSING: A NEW CONCEPT FOR IMPROVING POWER SYSTEM STABILITY

4.1 Introduction

Although selective-pole switching of double-circuit transmission lines would significantly improve power system stability as in Chapter 3, it has been seldom, if ever, used, for clearing line-to-line and double line-to-ground faults. The reason is the concern for the generator rotor body heating due to the negative sequence currents flowing in the generator as the result of the unbalanced operation during the dead time between fault clearing and line reclosing. Moreover, these negative sequence currents produce a double frequency (120 Hz) electromagnetic torque component which could excite one of the torsional frequencies of the turbine blades [39]. This might damage the turbine blades under such a resonance condition.

In this chapter, it is proposed to clear unsymmetrical faults, namely line-to-line, single and double line-to-ground faults on double-circuit transmission lines using selective-pole switching. The transmission system is then balanced during the dead time by using Thyristor Controlled Series Capacitors (TCSCs) in the interrupted phases (adaptive short-time compensation). Adaptive reclosing is then applied and the TCSCs are bypassed. The main advantages of such a scheme are as follows:

1. The pre-fault transmission system capacity is restored immediately after fault clearing not after reclosing. This will greatly enhance the system stability. It is worth noting that these faults represent more than 97% of transmission line faults [40].

2. Since the system is balanced, the adverse effects of the negative sequence currents are eliminated.

3. By using adaptive reclosure for reclosing these faults, the uninterrupted phase will
allow the identification of a sustained fault. This will eliminate the possibility of “ever” reclosing any of these faults into a permanent fault. This will add an additional improvement to the system stability.

4.2 Thyristor Controlled Series Capacitor

The Thyristor Controlled Series Capacitor (TCSC) shown in Figure 4.1 consists of a number of series connected modules [41,42]. In each module, the capacitor bank is provided with a parallel thyristor controlled inductor that circulates current pulses which add in phase with the line current. This boosts the capacitor voltage beyond the level that would be obtained by the line current alone. Each thyristor is triggered once per cycle and has a conduction interval that is shorter than a half-cycle of the rated frequency. The control and protection of TCSC are partitioned in two levels; common and module. Commands for both control and protective operations flow from the common level to the module levels. Status information is sent back from each module level. The design concept is to permit any module or combination of modules to be out of service while still being able to operate the remaining modules to benefit the power system.

The common-level protection detects problems affecting all modules, and as such, generally requires bypassing all modules with the bypass breaker. The module-level protection detects problems affecting a single-module and as such, may only initiate protective actions within the affected module. The thyristor switches allow for bypassing individual modules by continue gating the thyristors, and this is an effective protective action for many potential internal failures (e.g., capacitor failure). However, for some serious problems within a module (e.g., varistor failure), protective actions may involve bypassing all modules with the bypass breaker.

TCSC modules have three basic modes of operation: thyristor blocked (no gating and zero thyristor conduction), thyristor bypassed (continuous gating and full thyristor conduction), and operation in vernier mode with phase control of gate signals and consequent partial thyristor conduction. Figure 4.2 shows one module power circuit of TCSC. Figure 4.3 illustrates the first two modes. Part (a) shows the module with thyristors blocked, for which module impedance is just the capacitor reactance. Part (b)
MCP = Module Control and Protection
CCP = Common Control and Protection

Figure 4.1: Thyristor controlled series capacitor model.
Figure 4.2: One TCSC module power circuit.

Figure 4.3: Blocked and bypass operating modes: (a) thyristors blocked (no thyristor current), (b) thyristor-bypassed (full thyristor conduction).
shows a module operating in the thyristor-bypass mode. The thyristors are full conducting in this mode, so most of the line current flows through the thyristor path and the TCSC has a small net inductive impedance.

It is important to distinguish between two possible bypass modes with the TCSC. A breaker will typically be included across the TCSC, and when closed constitutes a "breaker-bypassed" mode. The thyristor bypass is used for control and many protective sequences, whereas the breaker bypass is used for protection due to internal TCSC failures or to remove the TCSC from service.

Figure 4.4 illustrates the two types (capacitive and inductive) of TCSC vernier operation with partial thyristor conduction. Part (a) shows the module operating with low levels of thyristor conduction. Circulating current results in a module capacitive impedance greater than the nominal capacitive reactance. Part (b) shows the module operating at high levels of conduction. The circulating current is reversed and the net impedance will be inductive.

Figure 4.4: Vernier operating modes with partial thyristor conduction: (a) capacitive vernier operation, (b) inductive vernier operation.
Since thyristor control can alter the impedance of the module, it is important to clarify certain terms:

\[
X_C = \text{"Nominal" reactance, of capacitor only}
\]

\[
I_{\text{Line}} = \text{Line current}
\]

\[
X_{\text{net}} = \text{Net reactance of TCSC, in per unit of } X_C, \text{ e.g. :}
\]

\[
X_{\text{net}} = +1.0 \text{ p.u. means operating with no thyristor current}
\]

\[
X_{\text{net}} = +1.5 \text{ p.u. means operating with thyristor firing such that the 60 Hz component of capacitor voltage is } 1.5 * X_C * I_{\text{Line}} \text{ and lags current by 90° (capacitive)}
\]

\[
X_{\text{net}} = -0.5 \text{ p.u. means operating with thyristor firing such that the 60 Hz component of capacitor voltage is } 0.5 * X_C * I_{\text{Line}} \text{ and leads current by 90° (inductive)}
\]

It is important to note that the impedance convention used here defines positive reactance as capacitive and negative reactance as inductive. Since these studies are concerned with a series capacitor, the capacitive direction is taken as positive ohms.

The TCSC capability can be illustrated in terms of reactance versus line current, as shown in Figure 4.5. This figure clearly shows the gap in control range between capacitive and inductive operation, as well as the reduction in dynamic range with increasing line current.

4.3 Principle of Adaptive Short-Time Compensation

The basic intent of the adaptive short-time compensation scheme is to balance the transmission system during the period between clearing and reclosing unsymmetrical faults using selective-pole switching. The operation sequence of such a scheme during a line-to-line or a double line-to-ground fault (Figure 4.6) is as follows [43]:

1. The detection of the fault, its type and the identification of the faulted phase(s) are carried out by the relaying system.

2. Two signals are provided by the relaying and control system, one for tripping the
faulted circuits \((a_1, b_1, \text{Figure 4.6})\), and the other for operating the TCSCs of phases A and B in the vernier mode (phase control of the gate signals and consequent partial thyristors conduction). The latter action will balance the transmission system if the TCSC is conducting such as its capacitive reactance is one half the inductive reactance of one circuit of the transmission line as shown in Figure 4.7.

### 4.4 Principle of Adaptive Selective-Pole Reclosing

Adaptive selective-pole reclosing of a transmission line is the controlling of its circuit breakers reclose sequence and timing based upon specific existing conditions on the transmission line [44]. A primary advantage of such a reclosing is that it can eliminate the possibility of reclosing the line into a permanent fault. This can be done
Figure 4.6: Principle of adaptive short-time compensation scheme.
by reclosing the tripped phases sequentially and measuring the voltage of the unenergized phases (Figure 4.8). The existence or nonexistence of a sustained fault can then be identified and the reclosing is aborted or permitted as appropriate. As an example, the sequence of operation during reclosing a transmission line tripped with selective-pole switching due to a line-to-line or double line-to-ground fault is as follows [45]:

1. If the voltage of either or both the unenergized conductors (a1, b1, Figure 4.8) is equal to zero, this indicates that a ground fault exists involving one or both these conductors (Figure 4.9(a)-(c)). In this case, the protective system will block the reclosing of the tripped conductors.

2. If the voltages of the energized phase (C) and either one of the unenergized conductors are equal, this indicates the existence of either a line-to-line fault between these two phases (Figure 4.9(d)-(e)) or a three-phase non-ground fault.

Figure 4.7: Transmission system equivalent circuit during adaptive short-time compensation of a line-to-line or double line-to-ground fault.
Figure 4.8: Principle of adaptive reclosing.
Figure 4.9: Induced voltages during adaptive reclosing.
(a solid connection developed after fault clearing between a₁, b₁ and phase C) as shown in Figure 4.9(f). The protective system action in this case is similar to that of (1).

3. The identification of the existence of a line-to-line fault between the unenergized conductors a₁ and b₁ cannot be done without reclosing one of them since the voltages of these two phases would be equal whether a fault exists between them or not (Figure 4.9(g)-(h)). By closing one of these two conductors (a₁) and bypassing the capacitor of that phase, the existence of a line-to-line fault could be indicated if the voltages of this phase and the unenergized conductor (b₁) are equal. In this case no further reclosing is permitted.

4. If no fault exists between these two conductors (a₁ and b₁), the voltage of the unenergized conductor (b₁) will be a small percentage (V₁) of the voltage of the energized phases. In this case, b₁ is reclosed and the capacitor of phase B is bypassed.

Figure 4.10 illustrates a general flow chart for the reclosing logic during the adaptive selective-pole reclosing of a transmission line during line-to-line or double line-to-ground fault.

Typical values of the voltages of the unenergized phases which is used to make a decision for adaptive reclosing during single phase energization of a transposed transmission line are given in Table 4.1 [46].

4.4.1 Adaptive Selective-Pole Reclosing of Single Line-to-Ground Faults

In the case of a single line-to-ground fault, it can be seen from Figure 4.11(a) that, if no fault exists, the voltage of the unenergized phase is neither zero nor equal to the voltage of the energized phases. In this case, reclosing the tripped phase is permitted. On the other hand, Figure 4.11(b) shows that in the case of a sustained fault, the voltage of the unenergized phase is equal to zero. In this case, the protective system would block the reclosing of this phase. A flow chart for the reclosing logic in the case of adaptive single-pole reclosure is illustrated in Figure 4.12.
Block reclosing of phases A and B

Fault exists

|VA| = 0
No

|VB| = 0
Yes

Reclose one phase (A)
at t_r and bypass TCSC of phase A

|VA| = |VC|
No

|VB| = |VC|
Yes

Fault exists

Block reclosing of phase B

Reclose the other phase (B) at t_r + Δt and bypass TCSC of this phase

Figure 4.10: Reclosing logic for identification system status during adaptive selective-pole reclosing of a transmission line (unfaulted phase: C).
Table 4.1: Voltages of unenergized phases during single phase energization of a transposed transmission line (line voltage: 765 kV, energized phase: A, $|V_A| = 1.0$ p.u.).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No fault</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>2</td>
<td>L-G fault (phase B)</td>
<td>0.00</td>
<td>0.04</td>
</tr>
<tr>
<td>3</td>
<td>L-G fault (phase C)</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>L-L fault (phases A and B)</td>
<td>1.00</td>
<td>0.11</td>
</tr>
<tr>
<td>5</td>
<td>L-L fault (phases A and C)</td>
<td>0.11</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td>L-L fault (phases B and C)</td>
<td>0.11</td>
<td>0.11</td>
</tr>
</tbody>
</table>

(a) C

V

B

V

A 1

(b)

C

V

B

V

A 0

Figure 4.11: Induced voltages during single-pole reclosing.

Figure 4.12: Adaptive single-pole reclosing logic.
Figure 4.13 summarizes the overall structure of the adaptive short time compensation and reclosing scheme.

4.5 Summary

In this chapter, an adaptive short-time compensation and reclosing technique for improving power system stability has been presented and its basic principles have been explained. The effectiveness of such a technique is investigated in the next chapter through simulation studies on the power system model of Figure 2.1.
Figure 4.13: Principle of the adaptive short-time compensation and reclosing scheme.
5. IMPACT OF ADAPTIVE SHORT-TIME COMPENSATION AND RECLOSING ON POWER SYSTEM TRANSIENT STABILITY

5.1 Introduction

This chapter presents the results of some simulation studies carried out to explore the effect of the adaptive short-time compensation and reclosing technique presented in Chapter 4 on power system stability. In this context, two TCSC banks designated as TCSC1 and TCSC2 were incorporated into the system under study as shown in Figure 5.1.

5.2 Simulation Results

5.2.1 Single and Multi-Phase Faults

The generator electromagnetic torques, load angles, speeds, the armature and field currents of generator G₁ during unsuccessful reclosing of a 4-30-4 cycles line-to-line fault (phases A&B, Line L₂ at F₁) are illustrated in Figure 5.2(a) for the case of triple-pole switching and in Figure 5.2(b) for the case of selective-pole switching with adaptive short-time compensation and reclosing. In the latter case, the TCSC1 of phases A and B are switched to the vernier mode just after fault clearing. Moreover, the persistence of the fault was detected and the reclosing was aborted. As it can be seen from Figure 5.2, the maximum generator swing angles, measured with respect to generator G₁, in the case of adaptive short-time compensation and reclosing (δ₁₂ = 36.61°, δ₁₃ = 29.24°) are less than that corresponding to the triple-pole switching (δ₁₂ = 46.97°, δ₁₃ = 49.10°). This is due to the fact that the adaptive short-time compensation and reclosing restored the pre-fault transmission system capacity just after fault clearing and prevented reclosing the tripped phases back into the fault. This resulted in a less acceleration of the generator rotors and improved the system stability. For a successful
Figure 5.1: System under study with the TCSC banks.
Figure 5.2: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G₁ during unsuccessful reclosing of a 4-30-4 cycles line-to-line fault on line L₂ at F₁: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure 5.2 (contd.): Generator electromagnetic torques, load angles, speeds, armature and field currents of generator $G_1$ during unsuccessful reclosing of a 4-30-4 cycles line-to-line fault on line $L_2$ at $F_1$: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure 5.3: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G₁ during successful reclosing of a 4-30 cycles line-to-line fault on line L₂ at F₁: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure 5.3 (contd.): Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G₁ during successful reclosing of a 4-30 cycles line-to-line fault on line L₂ at F₁: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
reclosing of the same fault, Figure 5.3 shows also a significant improvement in the system stability in the case of selective-pole switching with adaptive short-time compensation and reclosing compared to the case of triple-pole switching.

Figure 5.4 illustrates responses similar to that of Figure 5.2 except that the disturbance is an unsuccessful single-pole reclosing of a 4-30-4 cycles single line-to-ground fault (phase A). The system imbalance during the dead time is clearly noticeable in the electromagnetic torque response of generator G3 (Figure 5.4(a)). Figure 5.4 shows also a significant improvement in the system stability by using adaptive short-time compensation and reclosing. For a successful reclosing of the same fault, Figure 5.5 shows also a significant improvement in the system stability in the case of selective-pole switching with adaptive short-time compensation and reclosing compared to the case of single-pole switching.

5.2.2 Simultaneous Faults

The location of TCSC2 at the intermediate switching station between lines L4&L5 and L6&L7 can be utilized to balance the transmission system during the period between clearing and reclosing a fault on any one of these lines. Moreover, TCSC2 can also be used to balance the transmission system for simultaneous faults on both sides of the intermediate switching station. Consider the case of a single line-to-ground fault (a1) and a line-to-line fault (a1&b1) occurring simultaneously on lines L6 and L4 respectively (F4 and F3). Using selective-pole switching for tripping the faulted circuits, the virtual capacitive reactances of phases A and B of TCSC2 would be as shown in Figure 5.6. The generator electromagnetic torques, load angles, speeds, armature and field currents of generator G2 during unsuccessful reclosing of such a simultaneous fault (4-30-4 cycles) are illustrated in Figure 5.7 which shows again an improvement in the system stability by using adaptive short-time compensation and reclosing. For a successful reclosing of the same fault, Figure 5.8 shows also a significant improvement in the system stability in the case of selective-pole switching with adaptive short-time compensation and reclosing compared to the case of single and triple-pole switching.
Figure 5.4: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator $G_1$ during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line $L_2$ at $F_1$: (a) single-pole switching, (b) adaptive short-time compensation and reclosing.
Figure 5.4 (contd.): Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G₁ during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L₂ at F₁: (a) single-pole switching, (b) adaptive short-time compensation and reclosing.
Figure 5.5: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator $G_1$ during successful reclosing of a 4-30 cycles single line-to-ground fault on line $L_2$ at $F_1$: (a) single-pole switching, (b) adaptive short-time compensation and reclosing.
Figure 5.5 (contd.): Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G1 during successful reclosing of a 4-30 cycles single line-to-ground fault on line L2 at F1: (a) single-pole switching, (b) adaptive short-time compensation and reclosing.
5.2.3 Boosting the Transmission System Capacity

Another possible application of the TCSC is to boost the transmission system capacity beyond its normal value in the case of a severe disturbance. As an example, consider the case of a 4-cycle line-to-line fault on line L2 at F1 and a false 4-cycle three-pole tripping of line L1 with no reclosure. Figure 5.9(a) shows that the system is unstable for a 30-4 cycles unsuccessful reclosing of the line-to-line fault. On the other hand, Figure 5.9(b) demonstrates the effectiveness of employing the adaptive short-time compensation and reclosing technique (TCSC1 in this case) in maintaining the system stability. Moreover, as Figure 5.10(a) shows, the system exhibits a poor stability in the case of a 30-cycle successful reclosing of the same fault. Figure 5.10(b) shows that the adaptive short-time compensation and reclosing technique significantly improves the system stability in this case. It is worth noting here that TCSC1 can further improve the system stability by boosting the transmission capacity of lines L2 and L3 beyond its normal value. This is shown in Figure 5.11 in the form of introducing an
Figure 5.7: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G2 during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L6 at F4 and line-to-line fault on line L4 at F3: (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure 5.7 (contd.): Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G2 during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L6 at F4 and line-to-line fault on line L4 at F3: (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure 5.8: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G2 during successful reclosing of a 4-30 cycles single line-to-ground fault on line L6 at F4 and line-to-line fault on line L4 at F3: (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure 5.8 (contd.): Generator electromagnetic torques, load angles, speeds, armature and field currents of generator $G_2$ during successful reclosing of a 4-30 cycles single line-to-ground fault on line $L_6$ at $F_4$ and line-to-line fault on line $L_4$ at $F_3$: (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure 5.9: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator $G_1$ during unsuccessful triple-pole reclosing of a 4-30-4 cycles line-to-line fault on line $L_2$ at $F_1$ and a false 4-cycle three-pole tripping of line $L_1$ with no reclosing: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure 5.9 (contd.): Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G1 during unsuccessful triple-pole reclosing of a 4-30-4 cycles line-to-line fault on line L2 at F1 and a false 4-cycle three-pole tripping of line L1 with no reclosing: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure 5.10: Generator electromagnetic torques, load angles, speeds, armature and field currents of generator $G_1$ during successful triple-pole reclosing of a 4-30 cycles line-to-line fault on line $L_2$ at $F_1$ and a false 4-cycle three-pole tripping of line $L_1$ with no reclosing: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.

(a) 
(b)
Figure 5.10 (contd.): Generator electromagnetic torques, load angles, speeds, armature and field currents of generator G1 during successful triple-pole reclosing of a 4-30 cycles line-to-line fault on line L2 at F1 and a false 4-cycle three-pole tripping of line L1 with no reclosing: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
additional capacitive reactance $X_B$ in all the three phases. Figure 5.12 illustrates the generator load angle responses for the 4-30 cycles successful reclosing case of Figure 5.10 for four values of $X_B$. $X_B = 0$, represents the case illustrated in Figure 5.10(b). $X_B = 0.10X_L$ represents the case in which TCSC1 introduced an additional compensation of 10% in all the three phases of lines $L_2$ and $L_3$ and, therefore, boosted the transmission capacity of these lines beyond its normal values. As it can be seen from Figure 5.12, such a boosting enhances the power system stability.

5.3 Additional Results

Additional simulation studies were carried out on the study system of Figure 5.1 to verify the effectiveness of the adaptive short-time compensation and reclosing technique in enhancing power system stability. The results of these studies are presented in Appendix C.
Figure 5.12: Generator load angle responses during successful adaptive short-time compensation and reclosing of a 4-30 cycles line-to-line fault on line L₃ at F₁ and a false 4-cycle three-pole tripping of line L₁ with no reclosure.
5.4 Summary and Conclusion

In this chapter, studies have been performed to investigate the effect on power system stability of adaptive short-time compensation and reclosing of unsymmetrical faults on double-circuit transmission lines. Such an effect has been demonstrated through time-domain simulation studies on the sample multi-machine power system of Figure 5.1. The results of these studies have shown that adaptive short-time compensation significantly enhances the system stability as it restores the pre-fault transmission system capacity immediately after fault clearing. For that reason, reclosing of the tripped conductors can be delayed (the dead time can be increased) to ensure a complete secondary arc extinction. The benefit of using adaptive selective-pole reclosing in conjunction of adaptive short-time compensation for a further improvement of the system stability has been also demonstrated in this chapter. Moreover, it has been shown that vernier mode of operation of the TCSC could be used for boosting the transmission system capacity during severe disturbances.
6. SUMMARY AND CONCLUSIONS

6.1 Summary of the Thesis

Maintaining power system stability is very important to ensure continuous delivery of energy to customers. In this regard, the studies presented in this thesis were conducted to search for an economical and practical technique for enhancing power system transient stability during clearing and reclosing of unsymmetrical faults on double-circuit transmission lines.

A general introduction to the power system stability problem including physical concepts, classification, and definition of related terms is explained in Chapter 1. Analysis of elementary power system configurations by means of idealized models illustrates some of the fundamental stability properties of power systems.

In Chapter 2, the system used for the studies reported in this thesis is presented. Also the mathematical models of the various component of the system, namely the synchronous machine, the loads and transmission network are presented and the overall system structure is described. The modeling of the fault clearing process and mathematical formulation of the transient stability problem are also described in this chapter.

In Chapter 3, investigations are conducted to explore the impact of high-speed reclosing of transmission line faults on power system transient stability. Single and selective-pole switching techniques, are also introduced in this chapter.

Chapter 4 presents an adaptive short-time compensation and reclosing technique for improving power system stability during clearing and high-speed reclosing of unsymmetrical faults on double-circuit transmission lines. The fundamental concept of this technique is to interrupt these faults using selective-pole switching. The transmission system is then balanced using Thyristor Controlled Series Capacitors in the
interrupted phases. Adaptive reclosing is then applied to reclose the tripped phases and the TCSCs are bypassed. Since TCSC is a vital element of the proposed technique, a detailed description and modeling of such a FACTS device is presented in this chapter.

In Chapter 5, the effectiveness of the proposed adaptive short-time compensation and reclosing technique in improving the transient stability of the power system is demonstrated through time simulation studies. Boosting the transmission system capacity beyond its nominal value using TCSC is also presented in this chapter.

6.2 General Conclusions

The results of the studies conducted in Chapter 3 have demonstrated the benefit of using high-speed reclosing for improving power system transient stability. It has been also shown that selective-pole switching of unsymmetrical faults on double-circuit transmission lines significantly improves power system transient stability compared to triple-pole switching of the same faults. As these conclusions confirm previous research work results, the following can be regarded as original conclusions for the studies reported in this thesis:

1. The proposed adaptive short-time compensation technique enhances significantly the system stability by restoring the pre-fault transmission system capacity immediately after fault clearing.

2. Since the pre-fault transmission system capacity is restored immediately after fault clearing using adaptive short-time compensation, reclosing of the tripped conductors can be delayed (the dead time can be increased) to ensure a complete secondary arc extinction. This will increase the probability of a successful reclosure and further improve the system stability.

3. Since adaptive short-time compensation balances the system during the dead time, the adverse effects of the negative sequence currents are eliminated.

4. The proposed adaptive short-time compensation and reclosing scheme presented in this thesis is feasible and technically sound. It is worth noting,
however, that such a technique is applicable only for double-circuit transmission lines since balancing a single-circuit transmission line with an interrupted phase cannot be achieved with series connected devices.
REFERENCES


Appendix A
DATA OF THE SYSTEM UNDER STUDY

A.1 Synchronous Generator Data

Table A.1: Synchronous generator data.

<table>
<thead>
<tr>
<th>Generator</th>
<th>( G_1 )</th>
<th>( G_2 )</th>
<th>( G_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating MVA</td>
<td>2400</td>
<td>1000</td>
<td>1100</td>
</tr>
<tr>
<td>Rating kV</td>
<td>26</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td>( r_a ), p.u.</td>
<td>0.000</td>
<td>0.0045</td>
<td>0.0045</td>
</tr>
<tr>
<td>( x_f ), p.u.</td>
<td>0.130</td>
<td>0.1400</td>
<td>0.1200</td>
</tr>
<tr>
<td>( x_d ), p.u.</td>
<td>1.790</td>
<td>1.6500</td>
<td>1.5400</td>
</tr>
<tr>
<td>( x_q ), p.u.</td>
<td>1.710</td>
<td>1.5900</td>
<td>1.5000</td>
</tr>
<tr>
<td>( x_d' ), p.u.</td>
<td>0.169</td>
<td>0.2500</td>
<td>0.2300</td>
</tr>
<tr>
<td>( x_q' ), p.u.</td>
<td>0.228</td>
<td>0.4600</td>
<td>0.4200</td>
</tr>
<tr>
<td>( x_d'' ), p.u.</td>
<td>0.135</td>
<td>0.2000</td>
<td>0.1800</td>
</tr>
<tr>
<td>( x_q'' ), p.u.</td>
<td>0.200</td>
<td>0.2000</td>
<td>0.1800</td>
</tr>
<tr>
<td>( T_{d0} ), s.</td>
<td>4.300</td>
<td>4.500</td>
<td>3.7000</td>
</tr>
<tr>
<td>( T_q' ), s.</td>
<td>0.850</td>
<td>0.5500</td>
<td>0.4300</td>
</tr>
<tr>
<td>( T_{d0}'' ), s.</td>
<td>0.032</td>
<td>0.0400</td>
<td>0.0400</td>
</tr>
<tr>
<td>( T_{q0}'' ), s.</td>
<td>0.050</td>
<td>0.0900</td>
<td>0.0600</td>
</tr>
<tr>
<td>( x_o ), p.u.</td>
<td>0.130</td>
<td>0.1400</td>
<td>0.1200</td>
</tr>
<tr>
<td>( H ), s.</td>
<td>7.008</td>
<td>3.7030</td>
<td>3.1240</td>
</tr>
</tbody>
</table>
Figure A.1: System load flow (bus voltages are in p.u.).
## A.3 Transmission Line Data

### Table A.2: Transmission line data.

<table>
<thead>
<tr>
<th>Line parameter, $\Omega$/km</th>
<th>$Z_{T,L} = 0.01864 + j0.37280$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line length, km</td>
<td>$L_1 = 500, L_2 = L_3 = 300,$</td>
</tr>
<tr>
<td></td>
<td>$L_4 = L_5 = L_6 = L_7 = 200,$</td>
</tr>
<tr>
<td></td>
<td>$L_8 = 125, L_9 = 200$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transmission line voltage, kV</th>
<th>500</th>
</tr>
</thead>
</table>
Appendix B

THE ELECTROMAGNETIC TRANSIENTS PROGRAM

B.1 Introduction

The Electro-Magnetic Transients Program (EMTP) solves transient and steady state problems of multi-phase power systems. EMTP incorporates many power system equipment models including linear elements, transmission lines, transformers, synchronous generators, motors, sinusoidal sources, other types of sources than sinusoidal, breakers, diodes, thyristors, surge arresters, other non-linear elements and pi circuits. Other program features allow simulation of control systems (generator exciters, SVC thyristor switching, etc).

B.2 Applications of the EMTP

Studies involving the use of the EMTP can be put into two general categories. One is design, which includes insulation coordination, equipment ratings, protective device specification, control system design, power quality assessment, harmonic studies, etc. The other is solving operating problems such as unexplained outages or equipment failures. A partial list of typical EMTP studies follows:

1. Switching Surges
   - Deterministic
   - Probabilistic
   - Single-Pole Switching
   - High-Speed Reclosing
   - Capacitor Switching
   - Transient Recovery Voltages
• Cable Switching Transients and sheath protection

2. Lightning Surges
   • Backflash
   • Induced Surges
   • Incoming Surges at Stations

3. Insulation Coordination
   • Overhead Lines
   • Outdoor Stations
   • Gas-Insulated Substations
   • Arrester Duty

4. Shaft Torsional Stress
   • Subsynchronous Resonance
   • Switching-Induced

5. High Voltage DC (HVDC)
   • Controls
   • Electrical Transients
   • Harmonics

6. Static VAR Compensation
   • Controls
   • Overvoltages
   • Harmonics

7. Carrier Frequency Propagation

8. Harmonics

9. Ferroresonance

10. Series and Shunt Resonance

11. Motor Starting
12. Out-of-Phase Synchronization
13. Islanding or Other Disturbance Events
14. General Control Systems
15. Grounding
16. Asymmetrical Fault Current Evaluation
17. Phase Conductor Transposition
18. Ground Wire Losses
19. General Steady-State Analysis of Unbalanced Systems
20. Capacitor Bank Switching
21. Series Capacitor Protection

This is only a partial list. One of the EMTP's major advantages is its flexibility in modeling; an experienced user can apply the program to a wide variety of studies.

B.3 Program Capabilities - Overview

The EMTP is used to solve the ordinary differential and/or algebraic equations associated with an "arbitrary" interconnection of different electrical (power system) and control system components.

The implicit trapezoidal rule of integration is used in the discretization of the equations of most elements which are modeled by ordinary differential equations. The result is a set of real, simultaneous, algebraic equations which is solved at each time-step using advanced sparsity techniques. These equations are written in nodal-admittance form (with new unknown voltages as variables), and are solved by ordered triangular factorization. Numerical oscillations inherent to the trapezoidal rule of integration are eliminated using a procedure called CDA (Critical Damping Adjustment). CDA makes the simulation of power electronics devices simple and straightforward.

Initial conditions for differential equations of the various components can be determined automatically by the program for most cases of practical interest. The calculation of initial conditions is normally limited to linear elements. Nonlinear
resistances are always ignored during the steady-state solution. Nonlinear reactances can either be linearized during steady state or fully modeled to include harmonic distortion effects.

Injections of the electric network may also be specified in terms of power and voltage magnitude, thereby providing multi-phase load flow capability.

Control system modeling (TACS or Transient Analysis of Control Systems) allows for the superposition of an arbitrary number of linear phasor solutions of different frequencies. TACS is also used to simulate HVDC systems, SVCs, etc. A comprehensive library of such devices, including relay and CVT models, is included as part of the EMTP latest version (EMTP96).

Large sub-networks can be reduced into compact multi-port equivalents which are valid over a broad frequency range with the FDNE (Frequency Dependent Network Equivalent) support program.

Large coupled RLC networks, such as the internal transformer representation used by transformer manufacturers, can be manipulated internally without additional approximations or assumptions.

The measured response of a power transformer can be used to create frequency dependent transformer models using the HFT (High Frequency Transformer) model.

Support programs provide additional capabilities such as the calculation of overhead line and cable parameters, as well as the generation of more complex linear and nonlinear models for use in EMTP simulations.

Program output consists of component variables (e.g., branch currents or voltages, machine torques or speeds, etc.) as functions of time. Both printed and plotted outputs are available. Printed plots are simple character-based plots included in the standard printed output. Built-in plotted output is supported directly for Postscript printers. Otherwise, the EMTP has the support program EMTPOUT that produces screen and hardcopy plots of simulation results.

B.4 Program Input and Output

Basic data entry to the program is based on the "card image" paradigm; that is, a
flat ASCII file is created and modified with a standard editor, and column-sensitive data is entered according to the rules described in EMTP rule book.

The input file is read by the EMTP, and an output and/or plot files are generated as output. The plot file with the default extension "pl4" contains binary information that a support program such as EMTPOUT can read. The output file is a plain text file reporting various results of the simulation.

The input file contains the calculation time step, length of time to be simulated, and output requests, as well as the model data. The lumped branches are defined by resistance in ohms, inductance in mH or in ohms at power frequency, and capacitance in μF or in μS (micro-Siemens) at power frequency. The simplest traveling-wave models can be defined by surge impedances, resistance per unit length, wave velocity, and line length for positive and zero sequence. More complex line models require data that can only be generated with the help of support programs such as aux. Nonlinear elements are usually specified by current-and-voltage points for resistors, and current-and-flux-linkage points for inductors. Synchronous machine models use conventional stability data for the electrical side, and parameters in English units for the mechanical side. TACS input is specified by transferring information from the control block diagram to card images.

Most of the EMTP's input data requirements are different from, and more extensive than, other programs such as load flow, short-circuit, and stability. This is because the program is multiphase, it can simulate nonlinear elements, and generally uses more detailed models than the other programs. These features are needed to accurately simulate high frequency transients which occur during short time periods. Fortunately, there are auxiliary programs supplied with the EMTP which assist the user in setting up the input data for transmission lines, cables, transformers, surge arresters, and nonlinear inductors.

The primary output from a transient simulation includes plotted bus voltages, branch voltages, branch currents, branch energy dissipation, machine variables, and control system variables. These values can also be printed out as functions of time, but this type of output is often awkward to use. Printed maximum values of the variables
and the times at which they occurred are also available.

A steady-state phasor solution is performed before the transient simulation to determine the initial conditions, and this can also be a useful study tool in itself. Branch voltages and currents, bus voltages, power loss, and power flows are determined for the entire network. A frequency scan option is also available which systematically varies the frequency of the sources for the steady-state solution, and plots voltage magnitudes and angles as a function of frequency. This type of output is useful for harmonic and resonance studies.

B.5 Support Programs

Under DCG (Development Coordination Group) development, there has been a tendency to stay away from the super-program concept, where every feature is part of a single master program. EMTP96 now consists of the main computational engine "EMTP" and a number of support and auxiliary programs. These programs are:

<table>
<thead>
<tr>
<th>Program</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUX</td>
<td>Calculation of line and cable parameters, and EMTP model generation. Generation of power frequency transformer models, such as TRELEG, BCTRAN, and TOPMAG. Generation of data for hysteresis and eddy current models for power transformers. Calculation of instantaneous flux-current characteristics from RMS measurements.</td>
</tr>
<tr>
<td>FDNE</td>
<td>Generation of multi-port frequency dependent network equivalents.</td>
</tr>
<tr>
<td>FDBFIT</td>
<td>Generation of frequency dependent transformer model, primarily from measured data.</td>
</tr>
</tbody>
</table>
3FLOW Unbalanced three-phase load flow program.
EMTPOUT Output processing program.

B.6 Supported Hardware Platforms

EMTP96 supports a large variety of hardware platforms and operating systems, such as:

Intel-based PCs under Windows 3.1, Windows 95/98, Windows NT
DEC workstations under VMS and ULTRIX
DEC alpha under DEC UNIX
IBM RS6000/AIX
HP9000/UNIX-based
Sun/Solaris

With the exception of VAX VMS (which lacks graphical support), all platforms have approximately the same functionality and graphical output support. It is generally not necessary for the user to be aware of any programming idiosyncrasies due to differences in platforms and/or operating systems.

B.7 Example of an EMTP Data File

The following EMTP Data File was used to accomplish the results of Figure 3.2. It is important to mention here that the EMTP is a column sensitive, so the numbering of lines is very important for each data card (file name is ch3fig2.dat):

```
BEGIN NEW DATA CASE
CDA
C 1 2 3 4 5 6 7 8
C 34567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
C ----dt<---Tmax<---Xopt<---Copt<--Epsiln<--Tolmat<--Tstart
0.00005 2.0 60.0 60.0
C 1 2 3 4 5 6 7 8
C 34567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
C -Iprnt<--Iplot<-Idoub<-Kssout<-Maxout<-Ipun<-Memsav<-Icat<-Nenerg<-Iprsup
1 1 1 1 1 1 -1 3 0 0
```
C --Kchg<---Mult<---Kchg<---Mult<---Kchg<---Mult<---Kchg<---Mult<---Kchg<---Mult
1 1
C --Kchg<---Mult<---Kchg<---Mult<---Kchg<---Mult<---Kchg<---Mult
TACS HYBRID
C THE FOLLOWING TO COMPUTE THE ELECTRICAL TORQUE IN PER-UNIT
92T1
92T2
92T3
99T1PU = T1/6.36619772368
99T2PU = T2/2.65258238486
99T3PU = T3/2.91784062335
77T1PU 0.9497
77T2PU 0.8033
77T3PU 0.91198
33T1PU
33T2PU
33T3PU
C THE FOLLOWING TO COMPUTE THE POWER ANGLE
92D1
92D2
92D3
99D12 = (D1-D2)*180/PI
99D13 = (D1-D3)*180/PI
77D12 34.13
77D13 28.61
33D12
33D13
C *** ANOTHER WAY TO COMPUTE THE POWER ANGLE
92W1
92W2
92W3
99DELT2 58+W1 -W2 1.0 0.0 1.0
99DELT3 58+W1 -W3 1.0 0.0 1.0
99DELT2A2 = (DELT2*180/PI)+34.13
99DELT2A3 = (DELT3*180/PI)+28.61
77DELT2A2 34.13
77DELT2A3 28.61
33DELT2A2
33DELT2A3
C THE FOLLOWING TO COMPUTE THE SPEED OF THE MACHINES IN PER-UNIT
99W1PU = (W1/(2*PI*60))
99W2PU = (W2/(2*PI*60))
99W3PU = (W3/(2*PI*60))
THE FOLLOWING TO COMPUTE Ia, Ib, & Ic IN PER-UNIT

\[ I_{1APU} = \frac{Gen1A}{53293.8710021 \times \sqrt{2}} \]
\[ I_{1BPU} = \frac{Gen1B}{53293.8710021 \times \sqrt{2}} \]
\[ I_{1CPU} = \frac{Gen1C}{53293.8710021 \times \sqrt{2}} \]

\[ I_{2APU} = \frac{Gen2A}{22205.7795842 \times \sqrt{2}} \]
\[ I_{2BPU} = \frac{Gen2B}{22205.7795842 \times \sqrt{2}} \]
\[ I_{2CPU} = \frac{Gen2C}{22205.7795842 \times \sqrt{2}} \]

\[ I_{3APU} = \frac{Gen3A}{24426.3575426 \times \sqrt{2}} \]
\[ I_{3BPU} = \frac{Gen3B}{24426.3575426 \times \sqrt{2}} \]
\[ I_{3CPU} = \frac{Gen3C}{24426.3575426 \times \sqrt{2}} \]

THE FOLLOWING TO COMPUTE IF IN PER-UNIT

\[ IF_{1PU} = \frac{IF1}{1800.0} \]
\[ IF_{2PU} = \frac{IF2}{1800.0} \]
\[ IF_{3PU} = \frac{IF3}{1800.0} \]
C THE FOLLOWING TO COMPUTE I1D IN PER-UNIT

\[ I_{1D1} = \frac{I_{1D1}}{1800.0} \]

\[ I_{1D2} = \frac{I_{1D2}}{1800.0} \]

\[ I_{1D3} = \frac{I_{1D3}}{1800.0} \]

C THE FOLLOWING TO COMPUTE I1Q IN PER-UNIT

\[ I_{1Q1} = \frac{I_{1Q1}}{1800.0} \]

\[ I_{1Q2} = \frac{I_{1Q2}}{1800.0} \]

\[ I_{1Q3} = \frac{I_{1Q3}}{1800.0} \]

C THE FOLLOWING TO COMPUTE I2Q IN PER-UNIT

\[ I_{2Q1} = \frac{I_{2Q1}}{1800.0} \]

\[ I_{2Q2} = \frac{I_{2Q2}}{1800.0} \]

\[ I_{2Q3} = \frac{I_{2Q3}}{1800.0} \]

C THE FOLLOWING TO COMPUTE THE BUS VOLTAGES IN PER UNIT

90BUS1A
90BUS1B
90BUS1C
90BUS2A
90BUS2B
90BUS2C
90BUS3A
90BUS3B
90BUS3C
90BUS4A
90BUS4B
90BUS4C
90BUS5A
90BUS5B
90BUS5C
99V1APU = (BUS1A/(288675.134595*SQRT(2)))
99V1BPU = (BUS1B/(288675.134595*SQRT(2)))
99V1CPU = (BUS1C/(288675.134595*SQRT(2)))
99V2APU = (BUS2A/(288675.134595*SQRT(2)))
99V2BPU = (BUS2B/(288675.134595*SQRT(2)))
99V2CPU = (BUS2C/(288675.134595*SQRT(2)))
99V3APU = (BUS3A/(288675.134595*SQRT(2)))
99V3BPU = (BUS3B/(288675.134595*SQRT(2)))
99V3CPU = (BUS3C/(288675.134595*SQRT(2)))
33V1APU
33V1BPU
33V1CPU
33V2APU
33V2BPU
33V2CPU
33V3APU
33V3BPU
33V3CPU

C THE FOLLOWING TO COMPUTE THE BUS RMS VOLTEGES IN PER UNIT
99RMS1A 66+BUS1A 60.0
99RMS1B 66+BUS1B 60.0
99RMS1C 66+BUS1C 60.0
99RMS2A 66+BUS2A 60.0
99RMS2B 66+BUS2B 60.0
99RMS2C 66+BUS2C 50.0
99RMS3A 66+BUS3A 60.0
99RMS3B 66+BUS3B 60.0
99RMS3C 66+BUS3C 60.0
99RMS4A 66+BUS4A 60.0
99RMS4B 66+BUS4B 60.0
99RMS4C 66+BUS4C 60.0
99RMS5A 66+BUS5A 60.0
99RMS5B 66+BUS5B 60.0
99RMS5C 66+BUS5C 60.0
99VRMS1 = (RMS1A+RMS1B+RMS1C)/(3.0)
99V1PU = VRMS1/288675.1346
99VRMS2 = (RMS2A+RMS2B+RMS2C)/(3.0)
99V2PU = VRMS2/288675.1346
99VRMS3 = (RMS3A+RMS3B+RMS3C)/(3.0)
99V3PU = VRMS3/288675.1346
99VRMS4 = (RMS4A+RMS4B+RMS4C)/(3.0)
99V4PU = VRMS4/288675.1346
99VRMS5 = (RMS5A+RMS5B+RMS5C)/(3.0)
99V5PU  > VRMS/288675.1346
33V1PU
33V2PU
33V3PU
33V4PU
33V5PU
BLANK END OF TACS

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>345678901234567890123456789012345678901234567890123456789012345678901234567890</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>&quot;---Nodes--&gt;&quot;&lt;---Refer--&gt;&quot;&lt;--Ohms&lt;--Ohms&lt;---uS&lt;-----------------------------Output</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Bus1-&gt;Bus2-&gt;Bus3-&gt;Bus4--&gt;&lt;----R&lt;----L&lt;------C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>**************** LINE DATA *************</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>LINE # 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>BUS1A2BUS2A1</td>
<td>8.065 173.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>BUS1B2BUS2B1</td>
<td>8.065 173.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>8.065 173.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>LINE # 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>B1S1A4B1S4A1</td>
<td>5.3156109.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>B1S1B4B1S4B1</td>
<td>5.3156109.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>B1S1C4B1S4C1</td>
<td>5.3156109.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>LINE # 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>B2S1A4B2S4A1</td>
<td>5.3156109.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>B2S1B4B2S4B1</td>
<td>5.3156109.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>B2S1C4B2S4C1</td>
<td>5.3156109.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>LINE # 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>B1S2A6B1S6A2</td>
<td>3.6457 73.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>B1S2B6B1S6B2</td>
<td>3.6457 73.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>B1S2C6B1S6C2</td>
<td>3.6457 73.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>LINE # 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>B2S2A6B2S6A2</td>
<td>3.6457 73.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>B2S2C6B2S6C2</td>
<td>3.6457 73.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>LINE # 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>B1S6A5B1S5A6</td>
<td>3.6457 73.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>B1S6B5B1S5B6</td>
<td>3.6457 73.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>B1S6C5B1S5C6</td>
<td>3.6457 73.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>LINE # 7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>B2S6A5B2S5A6</td>
<td>3.6457 73.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>B2S6B5B2S5B6</td>
<td>3.6457 73.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>B2S6C5B2S5C6</td>
<td>3.6457 73.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>LINE # 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>BUS3A4BUS4A3</td>
<td>2.109946.401</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

118
BUS3B4BUS4B3  2.309946.401
BUS3C4BUS4C3  2.309946.401
C LINE # 9
BUS3A5BUS5A3  3.6457 73.74
BUS3B5BUS5B3  3.6457 73.74
BUS3C5BUS5C3  3.6457 73.74
C ...^......^......^......^......^XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C TRANSFORMER NO.1
TRANSFORMER T1A 9999
C BUS1->BUS2-> <--RK--<LK--<-NK
1GENT1A  0.00010.0001 26.0
2BUS1A  0.00010.0001 500.0
TRANSFORMER T1A T1B
C BUS1->BUS2-> <--RK--<LK--<-NK
1GENT1B 2BUS1B
TRANSFORMER T1A T1C
1GENT1C 2BUS1C
C TRANSFORMER NO.2
TRANSFORMER T2A 9999
C BUS1->BUS2-> <--RK--<LK--<-NK
1GENT2A  0.00010.0001 26.0
2BUS2A  0.00010.0001 500.0
TRANSFORMER T2A T2B
C BUS1->BUS2-> <--RK--<LK--<-NK
1GENT2B 2BUS2B
TRANSFORMER T2A T2C
1GENT2C 2BUS2C
C TRANSFORMER NO.3
TRANSFORMER T3A 9999
C BUS1->BUS2-> <--RK--<LK--<-NK
1GENT3A  0.00010.0001 26.0
2BUS3A  0.00010.0001 500.0
TRANSFORMER T3A T3B
C BUS1->BUS2-> <--RK--<LK--<-NK
1GENT3B 2BUS3B
TRANSFORMER T3A T3C
1GENT3C
**LOAD DATA**

**LOAD # 1 AT BUS #4**

- BUS4A: 163.5320.442
- BUS4B: 163.5320.442
- BUS4C: 163.5320.442

**LOAD # 2 AT BUS #5**

- BUS5A: 102.5612.821
- BUS5B: 102.5612.821
- BUS5C: 102.5612.821

**INJECTED Mvar**

- **500 Mvar AT BUS #4**
  - BUS4A: 1505.2
  - BUS4B: 1505.2
  - BUS4C: 1505.2
- **300 Mvar AT BUS #5**
  - BUS5A: 2000.0
  - BUS5B: 2000.0
  - BUS5C: 2000.0

**CONNECTING LINE #1 TO BUS #1**

- BUS1A BUS1A2: -10.0
- BUS1B BUS1B2: -10.0
- BUS1C BUS1C2: -10.0

**CONNECTING LINE #2 TO BUS #1**

- BUS2A BUS2A1: -10.0
- BUS2B BUS2B1: -10.0
- BUS2C BUS2C1: -10.0

**3 PHASE FAULT IN PHASE A, B, AND C AT BUS#1 (LINE #2) FOR 4 CYCLES**

- B1S1A4 B1S1B4: .1 .166666667
- B1S1A4 B1S1C4: .1 .166666667

**CONNECTING LINE #2 TO BUS #1**

- BUS1A B1S1A4: -10.0 .166666667
- BUS1B B1S1B4: -10.0 .166666667
- BUS1C B1S1C4: -10.0 .166666667
C **** CONNECTING LINE #7 TO BUS #6
BUS6A B2S6A5 -10.0 999.9
BUS6B B2S6B5 -10.0 999.9
BUS6C B2S6C5 -10.0 999.9
C **** CONNECTING LINE #7 TO BUS #5
BUS5A B2S5A6 -10.0 999.9
BUS5B B2S5B6 -10.0 999.9
BUS5C B2S5C6 -10.0 999.9
C **** CONNECTING LINE #8 TO BUS #3
BUS3A BUS3A4 -10.0 999.9
BUS3B BUS3B4 -10.0 999.9
BUS3C BUS3C4 -10.0 999.9
C **** CONNECTING LINE #8 TO BUS #4
BUS4A BUS4A3 -10.0 999.9
BUS4B BUS4B3 -10.0 999.9
BUS4C BUS4C3 -10.0 999.9
C **** CONNECTING LINE #9 TO BUS #3
BUS3A BUS3A5 -10.0 999.9
BUS3B BUS3B5 -10.0 999.9
BUS3C BUS3C5 -10.0 999.9
C **** CONNECTING LINE #9 TO BUS #5
BUS5A BUS5A3 -10.0 999.9
BUS5B BUS5B3 -10.0 999.9
BUS5C BUS5C3 -10.0 999.9
C **** CONNECTING TRANSFORMER #1 TO GENERATOR #1
GEN1A GENT1A -10.0 999.9
GEN1B GENT1B -10.0 999.9
GEN1C GENT1C -10.0 999.9
C **** CONNECTING TRANSFORMER #2 TO GENERATOR #2
GEN2A GENT2A -10.0 999.9
GEN2B GENT2B -10.0 999.9
GEN2C GENT2C -10.0 999.9
C **** CONNECTING TRANSFORMER #3 TO GENERATOR #3
GEN3A GENT3A -10.0 999.9
GEN3B GENT3B -10.0 999.9
GEN3C GEN3C -10.0 999.9
C ****************************Type-59 Synchronous Machine #1***************************
C 1 2 3 4 5 6 7 8
C 34567890123456789012345678901234567890123456789012345678901234567890
C <--Bus> <----VOLT><----FREQ><---ANGLE>
59GEN1A 22502.6458 60.0 0.0
GEN1B
GEN1C
C ****************************Type-59 Synchronous Machine #2***************************
C 1 2 3 4 5 6 7 8
C 34567890123456789012345678901234567890123456789012345678901234567890
C <--Bus> <----VOLT><----FREQ><---ANGLE>
131F1 2180.0 360.0 0.0
C 1 2 3 4 5 6 7 8
C 34567890123456789012345678901234567890123456789012345678901234567890
C <-Bus> <----VOLT><----FREQ><----ANGLE>
59GEN2A 22502.6458 60.0 -18.829
GEN2B
GEN2C
C ....^XX........^...............^       
PARAMETER FITTING 1.0
C 
C I1I2<NP><--SMOUTP><--SMOUTQ><----RMVA><----RKV><---AGLINE><-----S1><-----S2>
  1 2 1000.0 26.0 1800.
C ^^....^...............^...............^       
BLANK CARD SINCE NO SATURATION MODELLING
C ------Ra><------Xl><------Xd><------Xp><------X'd><------X'q><------X''d><------X''q>
   0.0045  0.140  1.650  1.590  0.250  0.460  0.200  0.200
C ^........^...............^...............^       
C ------T'do><------T'qo><------T'do><------T'qo><------Xo><------Rn><------Xn><------Xc>
   4.50  0.550  0.040  0.090  0.140
C ^........^...............^...............^       
C <----EXTRS><----HICO><----DSR><----DSM><----HSP><----DSD>
   1  1.0123659021
C XXXXXXXXXX........^...............^...............^       
BLANK END OF CLASS4 (MASS) DATA
C GA<4x><--N1><--N2><--N3><--N4><--N5><--N6>
   1  8 11 14
   2  1
   3  1
C ^XXXXX........^...............^...............^       
BLANK END OF CLASS5 (OUTPUT REQUEST) DATA
C CLASS 6 (OUTPUT REQUEST TO TACS)
C BUS-->xxxxxx<K1
  73IF2  4
  7311D2  5
  73I1Q2  6
  73I2Q2  7
  73T2  14
  74W2  2
  74D2  1
C ....^XXXXXX...^       
FINISH
C ****************************************Type-59 Synchronous Machine #3****************************************
C 1 2 3 4 5 6 7 8
C 34567890123456789012345678901234567890123456789012345678901234567890
C <-Bus> <----VOLT><----FREQ><----ANGLE>
59GEN3A 22078.0675 60.0 -21.593
GEN3B
GEN3C
C ............^XX.................^.............^  
PARAMETER FITTING 1.0  
C  ^......^  
C I212<NP><--SMOUTP><--SMOUTQ><--RMVA><--RKV><--AGLINE><--S1><--S2>  
1 1 2 1100. 26.0 1800.  
C ^......^  
BLANK CARD SINCE NO SATURATION MODELLING  
C --------Ra><------X1><------Xd><------Xp><------X'd><------X'q><------X'd><------X'q>  
0.0045 0.120 1.540 1.500 0.230 0.420 0.180 0.180  
C ^......^  
C --------T'do><------T'go><------T'do><------T'go><------Xo><------Rn><------Xn><------Xc>  
3.70 0.430 0.040 0.060 0.120  
C ^......^  
C  ^------EXTRS><------HICO><------DSR><------DSM><------HSP><------DSD>  
1 1.0114756106  
C XXXXXXXX..................^............................^  
BLANK END OF CLASS 4 (MASS) DATA  
C GA<4x><--N1><--N2><--N3><--N4><--N5><--N6>  
1 8 11 14  
2 1  
3 1  
C ^XXXXX.............^.............^.............^.............^.............^  
BLANK END OF CLASS 5 (OUTPUT REQUEST) DATA  
C CLASS 6 (OUTPUT REQUEST TO TACS)  
C BUS-->xxxxxx<K1  
73IF3 4  
73I1D3 5  
73I1Q3 6  
73I2Q3 7  
73T3 14  
74W3 2  
74D3 1  
C ........^xxxxxx..^  
FINISH  
C  
BLANK END OF SOURCES  
BLANK END OF NODAL OUTPUT  
BLANK END OF PLOT OUTPUT  
BEGIN NEW DATA CASE  
BLANK END OF ALL CASES
Appendix C
ADDITIONAL RESULTS

Figures C.1 and C.2 illustrate respectively the generator responses during unsuccessful (4-30-4 cycles) and successful (4-30 cycles) reclosing of a double line-to-ground fault (phase A&B) on line L2 at F1.

Figures C.3 and C.4 illustrate respectively the generator responses during unsuccessful (4-30-4 cycles) and successful (4-30 cycles) reclosing of a simultaneous line-to-line fault (phases A&B) on line L4 at F3 and single line-to-ground fault (phase C) on line L6 at F4.

Figures C.5 and C.6 illustrate respectively the generator responses during unsuccessful (4-30-4 cycles) and successful (4-30 cycles) reclosing of a simultaneous double line-to-ground fault (phases A&B) on line L4 at F3 and single line-to-ground fault (phase C) on line L6 at F4.
Figure C.1: Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles double line-to-ground fault on line L2 at F1: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.1: Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles double line-to-ground fault on line L2 at F1: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.1 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles double line-to-ground fault on line L2 at F1: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.1 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles double line-to-ground fault on line L2 at F1: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.1 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles double line-to-ground fault on line L2 at F1: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.1 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles double line-to-ground fault on line L2 at F1: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.1 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles double line-to-ground fault on line L2 at F1: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.2: Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles double line-to-ground fault on line L2 at F1: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.2 (contd.): Generator electromagnetic torques, load angles, speeds, armature
and rotor currents during successful reclosing of a 4-30 cycles
double line-to-ground fault on line $L_2$ at $F_1$: (a) triple-pole
switching, (b) adaptive short-time compensation and reclosing.
Figure C.2 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles double line-to-ground fault on line L₂ at F₁: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.2 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles double line-to-ground fault on line L₂ at F₁: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.2 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles double line-to-ground fault on line L2 at F1: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.2 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles double line-to-ground fault on line L2 at F1: (a) triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.3: Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30-4 cycles line-to-line fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.3 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L6 at F4 (phase C) and a 4-30-4 cycles line-to-line fault on line L4 at F3 (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.3 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30-4 cycles line-to-line fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.3 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30-4 cycles line-to-line fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.3 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L6 at F₄ (phase C) and a 4-30-4 cycles line-to-line fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.3 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L6 at F4 (phase C) and a 4-30-4 cycles line-to-line fault on line L4 at F3 (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.4: Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30 cycles line-to-line fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.4 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30 cycles line-to-line fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.4 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles single line-to-ground fault on line L6 at F4 (phase C) and a 4-30 cycles line-to-line fault on line L4 at F3 (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.4 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30 cycles line-to-line fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.4 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30 cycles line-to-line fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.4 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30 cycles line-to-line fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.5: Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L6 at F4 (phase C) and a 4-30-4 cycles double line-to-ground fault on line L4 at F3 (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.5 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30-4 cycles double line-to-ground fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.5 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L6 at F4 (phase C) and a 4-30-4 cycles double line-to-ground fault on line L4 at F3 (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.5 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L6 at F4 (phase C) and a 4-30-4 cycles double line-to-ground fault on line L4 at F3 (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.5 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30-4 cycles double line-to-ground fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.5 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during unsuccessful reclosing of a 4-30-4 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30-4 cycles double line-to-ground fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.6: Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30 cycles double line-to-ground fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.6 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles single line-to-ground fault on line L6 at F4 (phase C) and a 4-30 cycles double line-to-ground fault on line L4 at F3 (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.6 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30 cycles double line-to-ground fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.6 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30 cycles double line-to-ground fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.6 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles single line-to-ground fault on line L_6 at F_4 (phase C) and a 4-30 cycles double line-to-ground fault on line L_4 at F_3 (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.
Figure C.6 (contd.): Generator electromagnetic torques, load angles, speeds, armature and rotor currents during successful reclosing of a 4-30 cycles single line-to-ground fault on line L₆ at F₄ (phase C) and a 4-30 cycles double line-to-ground fault on line L₄ at F₃ (phases A&B): (a) single and triple-pole switching, (b) adaptive short-time compensation and reclosing.