Final Report
Security Assessment of Power Systems
Including Energy Storage
and with the
Integration of Wind Energy

Volume I

DOE Contract EC-77-S-02-4206
Purdue University

Digital Transient Simulation Effort
Consulting Agreement No. 1

Performed by

Power Math Associates, Inc.
Tempe, Arizona

Dr. P. M. Anderson
Principal Investigator

June 30, 1982

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Final Report
Digital Transient Simulation Effort

Table of Contents

	Page No.
1.0 Overview of Digital Simulation Effort	1
1.1 Host Program Selection	1
1.2 Analysis of the Purdue MOD-2 Model	2
1.2.1 The Mechanical System	3
1.2.2 The Electrical System	3
2.0 Digital Modeling of Synchronous Machines.	11
2.1 Basic Concepts of Machine Modeling for Stability	11
2.1.1 Synchronous Machine Saturation.	12
2.1.2 Test Problem.	15
2.2 Flux Linkage Model Representation.	16
2.2.1 Saturation of the Flux Linkage Model.	16
2.2.2 Simulation Results for the Flux Linkage Model	17
2.3 E'' Model Representation	19
2.3.1 Saturation of the E'' Model	20
2.3.2 Simulation Results for the E'' Model.	20
2.4 Simplified Saturation of the Flux Linkage Model.	23
2.5 Simplified Saturation of the E'' Model	23
2.6 Conclusions.	26
3.0 EPRI Stability Program Simulation	27
3.1 Digital Model of the Wind Turbine Generator.	27
3.2 Wind Model	34

3.3	Modular Modeling for Digital Simulation.	41
3.4	ETMSTAB Simulation of the Wind Generator	48
4.0	Conclusions	61
	References.	63
Appendix A.	Generator Simulation Results with Complete Saturation for a 10% Step Change in T_m	67
Appendix B.	Generator Simulation Results with Complete Saturation for a 5% Step Change in E_{FD}	111
Appendix C.	Generator Simulation Results for the Flux Linkage Model Comparing Full Saturation to Partial Saturation with Constant L_{MD} and L_{MQ}	155
Appendix D.	Generator Simulation Results Comparing Flux Linkage and E'' Models with the E'' Model Only Partially Saturated.	177
Appendix E.	Statistical Analysis of Differences in Generator Simulation Results.	199
Appendix F.	Modified ETMSTAB Subroutines.	257

LIST OF FIGURES

	Page
Figure 1.1	Block Diagram of MOD-2 Mechanical System. 4
Figure 1.2	Block Diagram of EPRI Program Generator System Component Definitions. 5
Figure 1.3	Block Diagram of the E'' Model. 9
Figure 1.4	Block Diagram of the Flux Linkage Model 10
Figure 2.1	Typical d-axis Open Circuit Saturation Curve. 13
Figure 3.1	Block Diagram of the Digital MOD-2 Model. 28
Figure 3.2	Power Coefficient as a Function of Gamma for Pitch Angles of (top to bottom) 0-36 degrees in 4 degree increments. 30
Figure 3.3	Wind Turbine Output Power vs Wind Velocity at Rated Blade Angular Velocity, Pitch Angles (top to bottom) of 0, 4, 8, 12, 16 and 20 degrees 31
Figure 3.4	Wind Turbine Torque-Speed Characteristic, Pitch Angles of 0-36 in 4 degree increments 32
Figure 3.5	Wind Turbine Power-Speed Characteristic, Pitch Angles of 0-36 in 4 degree increments 33
Figure 3.6	Block Diagram of Wind Model 36
Figure 3.7	Wind Model Simulation with $V_{WB} = 30$ mi/h (44 ft/s). 39

Figure 3.8	Wind Model Simulation with $V_{WB} = 30$ mi/h (44 ft/s) (a) Random Noise with $\Delta\omega = 0.5$; (b) Random Noise with $\Delta\omega = 0.5$, Ramp with $MAXR = 10$ mi/h, $T_{1R} = 5s$, $T_{2R} = 10s$, and Gust with $MAXG = 10$ mi/h, $T_G = 5s$, $T_{1G} = 15s$	40
Figure 3.9	Histogram of Random Noise Component with $\Delta\omega = 2.0$ rad/s.	42
Figure 3.10	Digital Implementation of the Notch Filter.	45
Figure 3.11	Nine Bus Test System; Top: Impedance Diagram, Bottom: Initial Conditions.	49
Figure 3.12	Wind Turbine Performance for Case WT01.	50
Figure 3.13	Wind Turbine Performance for Case WT02.	51
Figure 3.14	Wind Turbine Performance for Case WT03.	52
Figure 3.15	Wind Turbine Performance for Case WT04.	53
Figure 3.16	Wind Turbine Performance for Case WT05.	54
Figure 3.17	Wind Turbine Performance for Case WT06.	55
Figure 3.18	Wind Turbine Performance for Case WT07.	56
Figure 3.19	Wind Turbine Performance for Case WT08.	57
Figure 3.20	Wind Turbine Performance for Case WT09.	58
Figure 3.21	Wind Turbine Performance for Case WT10.	59
Figure A.1.a	T_m vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	68
Figure A.1.b	T_m vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	69
Figure A.2.a	E_{FD} vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	70

Figure A.2.b	E_{FD} vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	71
Figure A.3.a	V_t vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	72
Figure A.3.b	V_t vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	73
Figure A.4.a	I_a vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	74
Figure A.4.b	I_a vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	75
Figure A.5.a	T_e vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	76
Figure A.5.b	T_e vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	77
Figure A.6.a	$\Delta\omega$ vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	78
Figure A.6.b	$\Delta\omega$ vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	79
Figure A.7.a	δ vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	80
Figure A.7.b	δ vs time ini seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	81
Figure A.8.a	S_{gd} vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	82
Figure A.8.b	S_{gd} vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	83

Figure A.9.a	ψ_{AD} vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	84
Figure A.9.b	ψ_{AD} vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	85
Figure A.10.a	ψ_d vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	86
Figure A.10.b	ψ_d vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	87
Figure A.11.a	ψ_F vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	88
Figure A.11.b	ψ_F vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	89
Figure A.12.a	ψ_{kd} vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	90
Figure A.12.b	ψ_{kd} vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	91
Figure A.13.a	I_d vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	92
Figure A.13.b	I_d vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	93
Figure A.14.a	I_f vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	94
Figure A.14.b	I_f vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	95
Figure A.15.a	I_{kd} vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	96

Figure A.15.b	I_{kd} vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	97
Figure A.16.a	S_{gp} vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	98
Figure A.16.b	S_{gp} vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	99
Figure A.17.a	ψ_{AQ} vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	100
Figure A.17.b	ψ_{AQ} vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	101
Figure A.18.a	ψ_q vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	102
Figure A.18.b	ψ_q vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	103
Figure A.19.a	ψ_{kq} vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	104
Figure A.19.b	ψ_{kq} vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	105
Figure A.20.a	I_q vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	106
Figure A.20.b	I_q vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	107
Figure A.21.a	I_{kq} vs time in seconds, flux linkage model (a), step change in T_m , saturated (*) and unsaturated response .	108
Figure A.21.b	I_{kq} vs time in seconds, E'' model (b), step change in T_m , saturated (*) and unsaturated response .	109

Figure B.1.a	T_m vs time in seconds, flux linkage model (a), step change in EFD, saturated (*) and unsaturated response.	112
Figure B.1.b	T_m vs time in seconds, E'' model (b), step change in EFD, saturated (*) and unsaturated response.	113
Figure B.2.a	E_{FD} vs time in seconds, flux linkage model (a), step change in EFD, saturated (*) and unsaturated response.	114
Figure B.2.b	E_{FD} vs time in seconds, E'' model (b), step change in EFD, saturated (*) and unsaturated response.	115
Figure B.3.a	V_t vs time in seconds, flux linkage model (a), step change in EFD, saturated (*) and unsaturated response.	116
Figure B.3.b	V_t vs time in seconds, E'' model (b), step change in EFD, saturated (*) and unsaturated response.	117
Figure B.4.a	I_a vs time in seconds, flux linkage model (a), step change in EFD, saturated (*) and unsaturated response.	118
Figure B.4.b	I_a vs time in seconds, E'' model (b), step change in EFD, saturated (*) and unsaturated response.	119
Figure B.5.a	T_e vs time in seconds, flux linkage model (a), step change in EFD, saturated (*) and unsaturated response.	120
Figure B.5.b	T_e vs time in seconds, E'' model (b), step change in EFD, saturated (*) and unsaturated response.	121
Figure B.6.a	$\Delta\omega$ vs time in seconds, flux linkage model (a), step change in EFD, saturated (*) and unsaturated response.	122
Figure B.6.b	$\Delta\omega$ vs time in seconds, E'' model (b), step change in EFD, saturated (*) and unsaturated response.	123
Figure B.7.a	δ vs time in seconds, flux linkage model (a), step change in EFD, saturated (*) and unsaturated response.	124

- Figure B.7.b δ vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response. 125
- Figure B.8.a S_{gd} vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response. 126
- Figure B.8.b S_{gd} vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response. 127
- Figure B.9.a ψ_{AD} vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response. 128
- Figure B.9.b ψ_{AD} vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response. 129
- Figure B.10.a ψ_d vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response. 130
- Figure B.10.b ψ_d vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response. 131
- Figure B.11.a ψ_F vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response. 132
- Figure B.11.b ψ_F vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response. 133
- Figure B.12.a ψ_{kd} vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response. 134
- Figure B.12.b ψ_{kd} vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response. 135
- Figure B.13.a I_d vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response. 136
- Figure B.13.b I_d vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response. 137

Figure B.14.a	I_f vs time in seconds, flux linkage model (a), step change in EFD, saturated (*) and unsaturated response.	138
Figure B.14.b	I_f vs time in seconds, E'' model (b), step change in EFD, saturated (*) and unsaturated response.	139
Figure B.15.a	I_{kd} vs time in seconds, E'' model (b), step change in EFD, saturated (*) and unsaturated response.	140
Figure B.15.b	I_{kd} vs time in seconds, E'' model (b), step change in EFD, saturated (*) and unsaturated response.	141
Figure B.16.a	S_{gp} vs time in seconds, flux linkage model (a), step change in EFD, saturated (*) and unsaturated response.	142
Figure B.16.b	S_{gp} vs time in seconds, E'' model (b), step change in EFD, saturated (*) and unsaturated response.	143
Figure B.17.a	ψ_{AQ} vs time in seconds, flux linkage model (a), step change in EFD, saturated (*) and unsaturated response.	144
Figure B.17.b	ψ_{AQ} vs time in seconds, E'' model (b), step change in EFD, saturated (*) and unsaturated response.	145
Figure B.18.a	ψ_q vs time in seconds, flux linkage model (a), step change in EFD, saturated (*) and unsaturated response.	146
Figure B.18.b	ψ_q vs time in seconds, E'' model (b), step change in EFD, saturated (*) and unsaturated response.	147
Figure B.19.a	ψ_{kq} vs time in seconds, flux linkage model (a), step change in EFD, saturated (*) and unsaturated response.	148
Figure B.19.b	ψ_{kq} vs time in seconds, E'' model (b), step change in EFD, saturated (*) and unsaturated response.	149
Figure B.20.a	I_q vs time in seconds, flux linkage model (a), step change in EFD, saturated (*) and unsaturated response.	150

Figure B.20.b	I_q vs time in seconds, E'' model (b), step change in EFD, saturated (*) and unsaturated response.	151
Figure B.21.a	I_{kq} vs time in seconds, flux linkage model (a), step change in EFD, saturated (*) and unsaturated response.	152
Figure B.21.b	I_{kq} vs time in seconds, E'' model (b), step change in EFD, saturated (*) and unsaturated response.	153
Figure C.1	T_m vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	156
Figure C.2	E_{FD} vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	157
Figure C.3	V_t vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	158
Figure C.4	I_a vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	159
Figure C.5	T_e vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	160
Figure C.6	$\Delta\omega$ vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	161
Figure C.7	δ vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	162
Figure C.8	S_{GD} vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	163
Figure C.9	ψ_{AD} vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	164
Figure C.10	ψ_d vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	165

Figure C.11	ψ_F vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	166
Figure C.12	ψ_{kd} vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	167
Figure C.13	I_d vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	168
Figure C.14	I_F vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	169
Figure C.15	I_{kd} vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	170
Figure C.16	S_{Gq} vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	171
Figure C.17	ψ_{AQ} vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	172
Figure C.18	ψ_q vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	173
Figure C.19	ψ_{kq} vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	174
Figure C.20	I_q vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	175
Figure C.21	I_{kq} vs time in seconds, Simplified Flux Linkage Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	176
Figure D.1	T_m vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	178
Figure D.2	E_{FD} vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	179

Figure D.3	V_t vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	180
Figure D.4	I_a vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	181
Figure D.5	T_e vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	182
Figure D.6	$\Delta\omega$ vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	183
Figure D.7	δ vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	184
Figure D.8	S_{GD} vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	185
Figure D.9	ψ_{AD} vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	186
Figure D.10	ψ_d vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	187
Figure D.11	ψ_F vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	188
Figure D.12	ψ_{kd} vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	189
Figure D.13	I_d vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	190
Figure D.14	I_F vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	191
Figure D.15	I_{kd} vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	192

Figure D.16	S_{GQ} vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	193
Figure D.17	ψ_{AQ} vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	194
Figure D.18	ψ_q vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	195
Figure D.19	ψ_{kq} vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	196
Figure D.20	I_q vs time in seconds. Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	197
Figure D.21	I_{kq} vs time in seconds, Simplified E'' Model, Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}	198
Figure E.1.a.1	Statistical Plots of EA-EB for a T_m Disturbance, Data for T_e	206
Figure E.1.a.2	Statistical Plots of EA-EB for a T_m Disturbance, Data for $\Delta\omega$	207
Figure E.1.a.3	Statistical Plots of EA-EB for a T_m Disturbance, Data for δ	208
Figure E.1.a.4	Statistical Plots of EA-EB for a T_m Disturbance, Data for V_t	209
Figure E.1.b.1	Statistical Plots of EA-EB for a E_{FD} Disturbance, Data for T_e	210
Figure E.1.b.2	Statistical Plots of EA-EB for a E_{FD} Disturbance, Data for $\Delta\omega$	211
Figure E.1.b.3	Statistical Plots of EA-EB for a E_{FD} Disturbance, Data for δ	212

Figure E.1.b.4 Statistical Plots of EA-EB for a E_{FD} Disturbance,	
Data for V_t	213
Figure E.2.a.1 Statistical Plots of A-B for a T_m Disturbance,	
Data for T_e	216
Figure E.2.a.2 Statistical Plots of A-B for a T_m Disturbance,	
Data for $\Delta\omega$	217
Figure E.2.a.3 Statistical Plots of A-B for a T_m Disturbance,	
Data for δ	218
Figure E.2.a.4 Statistical Plots of A-B for a T_m Disturbance,	
Data for V_t	219
Figure E.2.b.1 Statistical Plots of A-B for a E_{FD} Disturbance,	
Data for T_e	220
Figure E.2.b.2 Statistical Plots of A-B for a E_{FD} Disturbance,	
Data for $\Delta\omega$	221
Figure E.2.b.3 Statistical Plots of A-B for a E_{FD} Disturbance,	
Data for δ	222
Figure E.2.b.4 Statistical Plots of A-B for a E_{FD} Disturbance,	
Data for V_t	223
Figure E.3.a.1 Statistical Plots of A-EA for a T_m Disturbance,	
Data for T_e	226
Figure E.3.a.2 Statistical Plots of A-EA for a T_m Disturbance,	
Data for $\Delta\omega$	227
Figure E.3.a.3 Statistical Plots of A-EA for a T_m Disturbance,	
Data for δ	228
Figure E.3.a.4 Statistical Plots of A-EA for a T_m Disturbance,	
Data for V_t	229

Figure E.3.b.1 Statistical Plots of A-EA for a E_{FD} Disturbance,	
Data for T_e	230
Figure E.3.b.2 Statistical Plots of A-EA for a E_{FD} Disturbance,	
Data for $\Delta\omega$	231
Figure E.3.b.3 Statistical Plots of A-EA for a E_{FD} Disturbance,	
Data for δ	232
Figure E.3.b.4 Statistical Plots of A-EA for a E_{FD} Disturbance,	
Data for V_t	233
Figure E.4.a.1 Statistical Plots of A-C for a T_m Disturbance,	
Data for T_e	236
Figure E.4.a.2 Statistical Plots of A-C for a T_m Disturbance,	
Data for $\Delta\omega$	237
Figure E.4.a.3 Statistical Plots of A-C for a T_m Disturbance,	
Data for δ	238
Figure E.4.a.4 Statistical Plots of A-C for a T_m Disturbance,	
Data for V_t	239
Figure E.4.b.1 Statistical Plots of A-C for a E_{FD} Disturbance,	
Data for T_e	240
Figure E.4.b.2 Statistical Plots of A-C for a E_{FD} Disturbance,	
Data for $\Delta\omega$	241
Figure E.4.b.3 Statistical Plots of A-C for a E_{FD} Disturbance,	
Data for δ	242
Figure E.4.b.4 Statistical Plots of A-C for a E_{FD} Disturbance,	
Data for V_t	243
Figure E.5.a.1 Statistical Plots of A-D for a T_m Disturbance,	
Data for T_e	246

Figure E.5.a.2 Statistical Plots of A-D for a T_m Disturbance,	
Data for $\Delta\omega$	247
Figure E.5.a.3 Statistical Plots of A-D for a T_m Disturbance,	
Data for δ	248
Figure E.5.a.4 Statistical Plots of A-D for a T_m Disturbance,	
Data for V_t	249
Figure E.5.b.1 Statistical Plots of A-D for a E_{FD} Disturbance,	
Data for T_e	250
Figure E.5.b.2 Statistical Plots of A-D for a E_{FD} Disturbance,	
Data for $\Delta\omega$	251
Figure E.5.b.3 Statistical Plots of A-D for a E_{FD} Disturbance,	
Data for δ	252
Figure E.5.b.4 Statistical Plots of A-D for a E_{FD} Disturbance,	
Data for V_t	253

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LIST OF TABLES

	Page
Table 1.1	Flux Linkage Form of Machine Equations. 7
Table 1.2	E'' Form of Machine Equations 8
Table 2.1	Flux Linkage Model Parameters 16
Table 2.2	Machine Inductance Dependence on L_{AD} and L_{AQ} for the E'' Model 22
Table 2.3	Machine Time Constants and Gains for the E'' Model. . . 23
Table 2.4	Sensitivity of Model Parameters to Saturation 25
Table 3.1	Statistics of Random Noise Component of Wind, Computed for $N = 50$, $\Delta\omega = 2.0$ 41
Table 3.2	Wind Turbine Governor Parameters. 46
Table 3.3	Special Model Parameters. 47
Table 3.4	Summary of Computer Runs of the Nine Bus System 48
Table E.1	Coding of Simulation Runs 202
Table E.2	Comparison Sets for Statistical Analysis. 203
Table E.3a	Statistical Analysis of the Difference between Flux Linkage and E'' Models, Unsaturated Case, Step Change in T_m 214
Table E.3b	Statistical Analysis of the Difference between Flux Linkage and E'' Models, Unsaturated Case, Step Change in E_{FD} 215
Table E.4a	Statistical Analysis of the Difference between Flux Linkage and E'' Models, Complete Saturation, Step Change in T_m 224

Table E.4b	Statistical Analysis of the Difference between Flux Linkage and E'' Models, Complete Saturation, Step Change in E_{FD}	225
Table E.5a	Statistical Analysis of the Difference between the Saturated (A) and Unsaturated (EA) Flux Linkage Model, Step Change in T_m	234
Table E.5b	Statistical Analysis of the Difference between the Saturated (A) and Unsaturated (EA) Flux Linkage Model, Step Change in E_{FD}	235
Table E.6a	Statistical Analysis of the Difference between the Flux Linkage Model when Fully Saturated and Partially Saturated, Step Change in T_m	244
Table E.6b	Statistical Analysis of the Difference between Flux Linkage Model when Fully Saturated and Partially Saturated, Step Change in E_{FD}	245
Table E.7a	Statistical Analysis of the Difference between the Flux Linkage (Saturated) Model and the E'' Model with Partial Saturation, Step Change in T_m	254
Table E.7b	Statistical Analysis of the Difference between Flux Linkage (Saturated) Model and the E'' Model with Partial Saturation, Step Change in E_{FD}	255

1.0 OVERVIEW OF THE DIGITAL SIMULATION EFFORT

The purpose of the PMA effort has been to adapt the MOD-2 simulation models, developed by Purdue University, for implementation on a digital transient stability program. This has involved several problems: selection of an appropriate host program, examination of the host program interface, analysis of the Purdue analog models for digital implementation, Fortran coding of the model equations, installation and debugging on the host program, and final model verification.

1.1 Host Program Selection

Our initial selection of the host stability code was the EPRI Diagnostic Program (DP), developed by Boeing Computer Services from a production stability codes [1,2]. There were several factors favoring use of the DP as a host program. The DP was developed as a modular test program, designed with complete independence of component models [1]. The DP was also well documented [2], both in terms of its performance accuracy, but also in terms of the exact steps required to implement new models. These are important considerations. Adding new code to an already large simulation is difficult. The added code segments must not only be correct, but must not interact with existing code in any way except as intended. This requires careful data management and coding precautions.

The DP was perceived to be a convenient solution because of its modular design, its unusually detailed documentation, and the availability of instruction manuals for code modification. These manuals were carefully followed in the early stages of the work to set up the appropriate table modifications for our intended code additions.

By mid-1981 new code developments in progress made the DP effort obsolete. EPRI had initiated, as part of RP 1208, a 'modular modeling package' to be implemented as part of a new Extended Transient-Midterm Stability Program (ETMSTAB). The older Transient Midterm Stability Program is itself a well documented, widely used program, developed by EPRI as RP 745 [3]. The extension of this original work by RP 1208 is not yet completed, but the modular feature was such an important development that it was clearly to our advantage in the present project to take advantage of these new features. EPRI and their contractor, BCS, agreed to our use of the new code, and provided assistance in our implementation of needed code revisions.

The modular modeling package permits the modeler to construct new component models by the concatenation of basic building blocks. This is similar to widely used continuous system modeling codes, such as CSMP or ACSL. The model building blocks available in the 1208 code provided all structures needed for the Purdue MOD-2 model except for the random number generator, which BCS provided.

1.2 Analysis of the Purdue MOD-2 Model

The Purdue MOD-2 model consists of the following subsystems:

1. wind model
2. blade dynamics
3. shaft dynamics
4. pitch control
5. generator model

The first four of these models may be considered the mechanical system and the generator model is the MOD-2 electrical system. We will discuss each system separately.

1.2.1 The Mechanical System. The mechanical system is shown in block diagram form in Figure 1.1. To implement this mechanical system into the existing code required a matching of subsystems already existing in ETMSTAB. These subsystem definitions are shown in Figure 1.2. ETMSTAB defines Generation System Components, such as SWING, TURBINE, and GOVERNOR to which the wind model must conform. To introduce the new mechanical model of the wind system requires the definition of new GOVERNOR and TURBINE blocks. The TURBINE block was constructed from linear components already defined in the modular modeling package. The wind GOVERNOR block required the creation of new nonlinear components for blade dynamics and the addition of a random number generator to allow specification of a random wind component as prescribed by Wasynczuk, et al [4]. The remainder of the wind mechanical system is as defined by Krause, et al [5,6]. Implementation required the revision of ETMSTAB subroutines APRINT, EVALG, GENEQT, INPUT, PREGOV, PRGOVH, and TSSSTP, modified versions of which are given in the Appendix F.

1.2.2. The Electrical System. The electrical system requiring the greatest effort was an adaptation of the MACHINE block of Figure 1.2 for the generator model specified by references 5 and 6, as documented thoroughly by private communication [7]. Since our original host program was the DP, a substantial effort was required to improve on the

Figure 1.2 Block Diagram of EPRI Program Generator System Component Definitions.

rather simple model provided in the host program. The equations provided by Purdue for the machine were adequate and complete, but indicated a more complex machine than that available in the DP. The linear portions of the model are simple and direct to implement, but considerable effort was spent on examining the best form for the equations so that saturation could be accurately and economically computed for each step in the digital solution.

Two forms of the machine equations were studied:

- (1) using E'_q , E'_d , and ψ_{kd} as states
- (2) using ψ_F , ψ_{kd} , and ψ_{kq} as states.

We shall refer to these models as the E'' model and the flux linkage model throughout the balance of this report.

The linear equations for each model are displayed in Tables 1.1 and 1.2. The E'' form of machine equation is similar to the structure usually employed in transient stability programs. Many forms of the equations are available, some with currents as inputs and some with voltages. In our testing, we used the form illustrated in Figure 1.3.

The flux linkage model, described fully in references 7 and 8, has the form shown in Figure 1.4. This form has certain advantages over the E'' model, as will be shown later. Our work consisted of comparing these models for ease of implementation and for accuracy of representation using simplified forms of saturation computation.

Table 1.1 Flux Linkage Form of Machine Equations [5,6]

Differential Equations

$$\frac{d\psi_F}{dt} = \frac{r_F L_{MD}}{\ell_F} \frac{\psi_d}{\ell_a} - r_F \left(1 - \frac{L_{MD}}{\ell_F}\right) \frac{\psi_F}{\ell_F} + r_F \frac{L_{MD}}{\ell_F} \frac{\psi_{kd}}{\ell_{kd}} + \frac{r_F}{L_{ADO}} E_{FD}$$

$$\frac{d\psi_{kd}}{dt} = r_{kd} \frac{L_{MD}}{\ell_{kd}} \frac{\psi_d}{\ell_a} + r_{kd} \frac{L_{MD}}{\ell_{kd}} \frac{\psi_F}{\ell_F} - r_{kd} \left(1 - \frac{L_{MD}}{\ell_{kd}}\right) \frac{\psi_{kd}}{\ell_{kd}}$$

$$\frac{d\psi_{kq}}{dt} = r_{kq} \frac{L_{MQ}}{\ell_{kq}} \frac{\psi_q}{\ell_a} - r_{kq} \left(1 - \frac{L_{MQ}}{\ell_{kq}}\right) \frac{\psi_{kq}}{\ell_{kq}}$$

Algebraic Equations

$$\psi_d = \frac{1}{\frac{r_a}{\ell_a} \left(1 - \frac{L_{MD}}{\ell_a}\right)} \left(r_a \frac{L_{MD}}{\ell_a} \frac{\psi_F}{\ell_F} + r_a \frac{L_{MD}}{\ell_a} \frac{\psi_{kd}}{\ell_{kd}} - \omega \psi_q - V_d \right)$$

$$\psi_q = \frac{1}{\frac{r_a}{\ell_a} \left(1 - \frac{L_{MQ}}{\ell_a}\right)} \left(r_a \frac{L_{MQ}}{\ell_a} \frac{\psi_{kq}}{\ell_{kq}} + \omega \psi_d - V_q \right)$$

$$T_e = I_q \psi_d - I_a \psi_q$$

Constants

$$1/L_{MD} = 1/L_{AD} + 1/\ell_a + 1/\ell_F + 1/\ell_{kd}$$

$$T_F = \ell_F / r_F$$

$$1/L_{MQ} = 1/L_{AQ} + 1/\ell_a + 1/\ell_{kq}$$

$$T_{kd} = \ell_{kd} / r_{kd}$$

$$T_{kq} = \ell_{kq} / r_{kq}$$

Table 1.2 E'' Form of Machine Equations [8]

Differential Equations

$$T'_{do} \frac{dE'_q}{dt} = \frac{L_{AD}}{L_{ADO}} E_{FD} - (1+K_d) E'_q + K_d \psi_{kd} + x_{kd} I_d$$

$$T'_{qo} \frac{dE'_d}{dt} = -E'_d - (x_q - x'_q) I_q$$

$$T'_{do} \frac{d\psi_{kd}}{dt} = -\psi_{kd} + E'_q + (x'_d - x_\ell) I_d$$

Algebraic Constraints

$$E'_q = K_1 E'_q + K_2 \psi_{kd}$$

$$V_d = E'_d - I_q X'_q - I_d r$$

$$T_e = E'_q I_q + E'_d I_d$$

$$V_q = E'_q r - I_q X'_d + I_d X'_q$$

Derived Constants

$$K_d = \frac{(L_d - L'_d)(L'_d - L'_d)}{(L'_d - \ell_a)^2}$$

$$T'_{do} = \frac{L_{AD} + \ell_F}{r_F}$$

$$K_1 = \frac{L'_d - \ell_a}{L'_d - \ell_a}$$

$$T'_{do} = \frac{1}{r_{kd}} (\ell_{kd} + L_{AD} - \frac{L_{AD}^2}{L_{AD} + \ell_F})$$

$$K_2 = 1 - K_1$$

$$x_{xd} = \frac{(L_d - L'_d)(L'_d - \ell_a)}{L'_d - \ell_a}$$

$$T'_{q} = \frac{L_{AR} + \ell_{kq}}{r_{kq}}$$

Figure 1.3 **Block Diagram of the E'' Model.**

Figure 1.4 Block Diagram of the Flux Linkage Model

2.0 DIGITAL MODELING OF SYNCHRONOUS MACHINES

This section presents an analysis of synchronous machine equations, with particular emphasis on numerical solution. The basic machine model is that used by Purdue for their simulation of the MOD-2 generation [5,6]. This model ignores the derivative (p) terms and assumes constant generator angular velocity. These assumptions are consistent with current theory on synchronous machine modeling that neglect stator transients [9-14]. Our treatment follows these published assumptions, except for our adherence to the international standard conventions for describing synchronous machines [15].

2.1 Basic Concepts of Machine Modeling for Stability Studies

Power system transient stability involves the interaction of rotating machines of similar inertias following a severe disturbance that causes the displacement of one or more machines. The oscillations that follow the disturbance are poorly damped and usually have frequencies of oscillation of below 5 hertz. Machine models must faithfully describe synchronous generator behavior in this restricted bandwidth.

Another requirement of the generator model is the need for compatibility with the models that represent the balance of the power system. Since network transients are very fast with respect to electromechanical transients, the network is solved algebraically in transient stability studies. Since derivative (p_ψ) terms are neglected in the networks, they should also be neglected in the stator of the machine. In studies made for this project the stator transients were neglected throughout.

Because stator transients are neglected and only balanced disturbances are assumed, an artificial method of simulating the fault damping due to dc offset must be provided. This is usually done as shown in Figures 3 and 4 by the introduction of a speed feedback term (D) in the accelerating torque calculation.

2.1.1 Synchronous Machine Saturation. Saturation is an important nonlinearity that must be included in the modeling of synchronous machines. Our approach to modeling saturation is presented briefly to provide background information for the results that follow.

We make the basic assumption that saturation in the d and q axes is uncoupled and can be treated separately. This is not really true, since saturation of one axis affects the other axis through the torque equation. Some modelers combine the fluxes in a Euclidean way to compute a total flux, which is used as the basis for saturation [16]. Others treat the saturation in the two axes separately, as we do here. The 'best' method is considered a subject for research beyond the scope of our work.

Consider the d-axis saturation curve shown in Figure 2.1, where we plot the flux linkage λ_D vs the current flowing through L_{AD} . We assume the leakage inductances are constant and that only L_{AD} saturates. Note that saturation starts to have an effect at a threshold value A and increases in some nonlinear, monotonic manner for values of flux linkage greater than the threshold.

Now define the saturation function

$$S_{GD} = \frac{\Delta I_M}{I_{MO}} \quad (2.1)$$

Figure 2.1 Typical d-axis Open Circuit Saturation Curve

Then $\Delta I_M = S_{GD} I_M$ or

$$\Delta I_M = \frac{S_{GD} \psi_{AD}}{L_{AD}} \quad (2.2)$$

The saturation function S_{GD} is usually approximated by either a quadratic or exponential function. For example, let

$$S_{GD} = \begin{cases} \frac{B(\psi_{AD} - A)^2}{\psi_{AD}} & \psi_{AD} > A \\ 0 & \psi_{AD} < A \end{cases} \quad (2.3)$$

Then, we may compute

$$\begin{aligned} \psi_{AD} &= L_{AD} I_{M0} = L_{AD} (I_M - \Delta I_M) \\ &= L_{AD} I_M - S_{GD} \psi_{AD} \end{aligned}$$

or

$$\psi_{AD} = \frac{L_{AD}}{1 + S_{GD}} I_M \quad (2.4)$$

Equation (2.4) says that, in terms of the total current I_M flowing through the nonlinear inductance L_{AD} , the total flux linkage ψ_{AD} behaves as if L_{AD} were replaced by a smaller inductance $L_{AD}/(1 + S_{GD})$. This smaller inductance is the slope of the ψ vs I line passing through the operating point, as shown in Figure 2.1. Thus, if S_{GD} is computed by a formula such as (2.3), L_{AD} may be modified as required to continually reflect the saturation of the d axis. We treat the q axis similarly, modifying L_{AQ} by a similar saturation function S_{GQ} .

In the digital solution of the differential equations, the computation at each time step is complicated by the implicit nature of the nonlinear equations. Thus, flux linkages may be known (at the completion of a time step) from which currents may be computed. But flux linkages are nonlinear functions of currents and saturation, and are therefore functions of the saturated flux linkages. We solve this problem by computing saturation functions S_{GD} and S_{GQ} at the end of each time step explicitly and then use these saturations for the next time step. We assume that this introduces negligible error since the time steps are small and the changes in S_G are smooth and slowly varying.

2.1.2 Test Problem. To test simulation results we devise a system consisting of a single machine connected through a transmission line to an infinite bus. We excite the system by making step changes in the mechanical torque T_M or the excitation voltage E_{FD} . The observed results are plotted and compared.

Details of the one machine system are given in Anderson and Fouad [8], Chapter 5, for both analog and digital simulations. Here, our machine model is simplified, as discussed previously, but the line constants and initial conditions as given in reference 5. The initial conditions are rated load at rated power factor with 1.0 per unit voltage at the infinite bus. This requires high initial machine voltage with heavy saturation, and provides a good test of saturated vs unsaturated conditions.

Data for the test machine are values taken from [8]. These values were used for our comparison studies so that results could be benchmarked against known solutions.

2.2 Flux Linkage Model Representation

The flux linkage model simulated in our tests is exactly that used by Purdue, and is described by the equations of Table 1.1. A block diagram of the model is shown in Figure 1.4. Our simulation did not neglect the $\Delta\omega$ terms, a fact that we realized only after the plotting was completed. The simulation would have been improved, according to well established theory, had we neglected this term [12].

2.2.1 Saturation of the Flux Linkage Model. As noted in Figure 1.4, the only terms that are functions of saturation are the inductances L_{AD} , L_{AQ} , L_{MD} , and L_{MQ} . Saturation functions were computed at each time step and revised values used for the succeeding time step. The relationship between the model parameters and the saturating inductances is shown in Table 2.1. Using the relationships of Table 2.1 we may compute the

Table 2.1 Flux Linkage Model Parameters

Parameter	Dependence on L_{AD} or L_{AQ}
L_{MD}	$\frac{1}{1/L_{AD} + 1/\ell_a + 1/\ell_F + 1/\ell_{kd}}$
L_{MQ}	$\frac{1}{1/L_{AQ} + 1/\ell_a + 1/\ell_{kq}}$

sensitivity of L_{MD} and L_{MQ} to changes in L_{AD} and L_{AQ} by taking the total differential.

$$\Delta L_{MD} = \frac{\partial L_{MD}}{\partial L_{AD}} \Delta L_{AD} = \frac{L_{MDO}^2}{L_{ADO}^2} \Delta L_{AD} \quad (2.5)$$

$$\Delta L_{MQ} = \frac{\partial L_{MQ}}{\partial L_{AQ}} \Delta L_{AQ} = \frac{L_{MQO}^2}{L_{AQO}^2} \Delta L_{AQ} \quad (2.6)$$

where the zero subscript refers to the unsaturated value. Then we may compute

$$L_{MD} = L_{MDO} - \frac{L_{MDO}^2 S_{GD}}{L_{ADO}(1 + S_{GD})} \quad (2.7)$$

with a similar result for L_{MQ} . Computing the percent change in L_{MD} at full rated load operation, we find that L_{MD} varies less than 1%. Thus L_{MD} and L_{MQ} are rather insensitive to changes in saturation. This is fortunate since these parameters are often treated as constants, such as in potentiometer settings on the analog computer.

2.2.2 Simulation Results for the Flux Linkage Model. Simulated results for the flux linkage model are presented in Appendices A and B, where they are arranged for comparison with the E'' model. Appendix A presents the results due to a 10% increase in mechanical torque T_m with constant excitation. Appendix B shows the effect of a 5% increase in E_{FD} with constant mechanical torque. All variables are plotted twice, once over the 0 - 2.5s range and once for 0 - 25.0s. The two plots show the different time constants of the responses effectively.

A step change in either E_{FD} or T_m produces an oscillating response, the frequency of which depends on the machine parameters, the inertia

constant of the rotating shaft, and the machine loading. Since the simulated disturbances are relative small we can estimate the frequency of oscillation by examining a linear machine model [8, Chap. 5]. Thus we write, in the s domain,

$$\begin{aligned} s E'_q &= -(1/K_3\tau_{d0}) E'_q - (K_4/\tau_{d0})\delta + (1/\tau_{d0}) E_{FD} \\ s \omega &= -(K_2/\tau_j) E'_q - (K_1/\tau_j) \delta + (1/\tau_j) T_m \\ s \delta &= \omega_B \omega \end{aligned} \tag{2.8}$$

Solving for ω , we have

$$\omega = \frac{-K_2 s E_{FD}}{\tau_j \tau_{d0} \phi(s)} + \frac{(1 + K_3 \tau_{d0} s) s T_m}{K_3 \tau_j \tau_{d0} \phi(s)} \tag{2.9}$$

where $\phi(s)$ is the characteristic equation

$$\phi(s) = s^3 + (1/K_3\tau_{d0})s^2 + (\omega_B K_1/\tau_j)s + \frac{\omega_B(K_1K_4 - K_2K_3)}{K_3K_4\tau_j\tau_{d0}} \tag{2.10}$$

For the machine and condition simulated, we have the constants [8],

$$\begin{aligned} K_1 &= 1.4479 & K_4 &= 1.8050 \\ K_2 &= 1.3174 & \tau_{d0} &= 5.9 \text{ s} \\ K_3 &= 0.3072 & \tau_j &= 4.74 \text{ s} \end{aligned}$$

Substituting into (2.10) we compute

$$\begin{aligned}
\phi(s) &= s^3 + 0.5517 s^2 + 115.1735s + 53.6848 \\
&= (s + 0.4663)(s + 0.0427 \pm j 10.7300) \\
&= (s + 0.4663)(s^2 + 0.0854s + 10.7301)
\end{aligned} \tag{2.11}$$

The response will be greatly underdamped and will oscillate at a frequency of 10.7 rad/s or about 1.7 Hz (period of oscillation = 0.58s). The damping ratio is computed to be 0.0044.

Oscillations of almost exactly 1.7 Hz are observed in nearly all plots. The step change in T_m excites this mode of oscillation markedly, with nearly all variables showing this characteristic oscillation. Only the terminal voltage fails to show a strong oscillation.

When excited by a step change in E_{FD} , the oscillatory behavior is present, but to a lesser degree. Indeed, many variables exhibit almost a first order response. The speed is oscillatory, however, as predicted by (2.9).

The effect of saturation is clearly evident in all variables plotted in Appendices A and B. For stability simulations, the most important variables are T_e and ω , since these variables reflect the ability of the machine to maintain synchronism. It is interesting to note that these variables are hardly affected by saturation at all.

The network interaction is also important, and this is best illustrated by examining V_t and I_a . V_t is greatly affected by saturation, largely because this machine has no exciter. The terminal current is different for the saturated case with a step in E_{FD} because the excitation change is less effective in producing more reactive power in the saturated condition.

2.3 E'' Model Representation

The E'' model is important to study carefully since this model, or very similar models, are in common use in digital stability simulations. All of the current generation of large scale simulations employ models of similar structure to the E'' model, using currents or voltages as states in preference to flux linkages.

The response of this model to changes in T_m and E_{FD} are displayed in Appendices A and B, respectively. The displays are arranged for ease of comparison with the flux linkage model and the results are observed to be nearly identical. This is to be expected since exactly the same assumptions are made in each model and only the choice of state variables is different. The method of treating saturation, however, is greatly different.

2.3.1 Saturation of the E'' Model. In the flux linkage model, saturation is easily introduced by replacing L_{AD} by $L_{AD}/(1+S_{GD})$ at every time step, with similar treatment in the q axis. Since L_{AD} and L_{AQ} appear in very few terms of the equations, this modification is simple and direct. None of the time constants in the flux linkage model vary with saturation.

For the E'' model, the inclusion of saturation is much more complex. Almost every inductance and time constant in this model is a function of L_{AD} or L_{AQ} . This means that nearly every 'constant' term in every equation must be modified at each time step in the dynamic solution. (Refer to Table 1.2 to review these equations). The dependence of inductances, time constants, and gains on L_{AD} and L_{AQ} is shown in Tables 2.2 and 2.3.

Our approach to the E'' model is to recompute the parameters of Tables 2.2 and 2.3 at each time step in the digital solution. This gives assurance that saturation is treated correctly and the result is seen to be almost exactly the same as for the flux linkage model.

2.3.2 Simulation Results for the E'' Model. An examination of Appendices A and B show that the two models perform almost identically. Any visual comparison of the two simulations leads one to the conclusion that the models are very similar in performance.

In order to provide a quantitative comparison, the computed step-by-step results were subtracted to give a difference for each variable as a function of time. We then analyzed this difference variable statistically, using 126 data points from the time domain simulation.

A statistical comparison of these differences is given in Appendix E, where several cases are compared against the saturated flux linkage model. Table E4 and Figure E2 show results of the comparison between the saturated flux linkage and E'' model. All error measures are very small and indicate a satisfactory model comparison. This fact merely confirms the visual comparison in Appendices A and B, but does so quantitatively.

An outside bound on saturation error is provided by a comparison between saturated and unsaturated models, shown in Figure E3 and Table E5.

2.4 Simplified Saturation of the Flux Linkage Model

Simulation results of the flux linkage model with a simplified saturation is shown in Appendix C. The simplified saturation makes use

Table 2.2 Machine Inductance Dependence on L_{AD} and L_{AQ}
for the E'' model

$L'_d = x_d$	$L_{AD} + \ell_a - \frac{L_{AD}^2}{L_{AD} + \ell_F}$
$L'_d = x''_d$	$L_{AD} + \ell_a - \frac{L_{AD}^2(\ell_F + \ell_{kd})}{\ell_F \ell_{kd} + L_{AD}(\ell_F + \ell_{kd})} = \frac{\ell_a}{\ell_a - L_{MD}}$
$L''_q = x''_q$	$L_{AQ} + \ell_a - \frac{L_{AQ}^2}{L_{AQ} + \ell_{kq}} = \frac{\ell_a^2}{\ell_a - L_{MQ}}$
L_{MD}	$\frac{1}{1/L_{AD} + 1/\ell_a + 1/\ell_F + 1/\ell_{kd}}$
L_{MQ}	$\frac{1}{1/L_{AQ} + 1/\ell_a + 1/\ell_{kq}}$
x_{xd}	$\frac{(L_d - L'_d)(L'_d - \ell_a)}{L'_d - \ell_a}$
Z^2	$r^2 + x''_d x''_q$

Table 2.3 Machine Time Constants and Gain
Constants for the E'' Model

T'_{do}	$(L_{AD} + \ell_F) / r_F$
T''_{do}	$\frac{L_{AD} + \ell_{kd} - L_{AD}^2}{r_{kd} (L_{AD} + \ell_F)}$
T''_{qo}	$(L_{AQ} + \ell_{kq}) / r_{kq}$
K_1	$\frac{L'_d - \ell_a}{L'_d - \ell_a}$
K_2	$1 - K_1$
K_d	$\frac{(L_d - L'_d)(L'_d - L''_d)}{(L'_d - \ell_a)^2}$

of the fact that, from equation (2.7), L_{MD} varies only slightly with saturation. This suggests that the simulation might hold L_{MD} , L_{MQ} , L_{AD} , and L_{AQ} constant, but still modify ψ_{AD} and ψ_{AQ} using the same saturation function. This is the way saturation is usually applied in the analog computer.

The results of this simplified saturation model are disappointing, as shown in Appendix C. The statistical analysis of Appendix E shows that the simplified model has almost the same error as the unsaturated case.

This approach was not pursued further to determine the reasons for the observed results. The digital simulation of the flux linkage model with complete saturation is so simple that there is little need for a reduction in complexity.

2.5 Simplified Saturation of the E'' Model

An analysis of the parameters for the E'' model suggest that it may not be necessary to saturate every term in Tables 2.2 and 2.3 in order to get satisfactory results. Computation of the total differentials of all inductances, time constants, and gains shows that most of these parameters are relatively insensitive to saturation. We explore this concept further in an attempt to identify a simpler saturation model.

Table 2.4 summarizes the sensitivity of the E'' model parameters to changes in L_{AD} and L_{AQ} and gives the percent change between saturated and unsaturated values at full load. Only five parameters, marked by an asterisk in Table 2.4, show any marked variation due to saturation. This suggests that a satisfactory model might be devised where only these five parameters are treated for saturation.

The results of the simplified saturation, modifying only the five parameters, is given in Appendix D. The simulations plotted would appear to have only one quantity plotted, but actually show two plots:

Table 2.4 Sensitivity of Model Parameters to Saturation

Parameter	Saturation Dependence	% Change
L_d	$L_{do} - \frac{S_{GD}L_{ADO}}{1+S_{GD}}$	-21. *
L'_d	$L'_{do} - \frac{S_{GD}L_{ADO}}{1+S_{GD}} \left(\frac{\ell_F}{\ell_F+L_{ADO}} \right)$	-1.55
L''_d	$L''_{do} - \frac{S_{GD}L_{ADO}}{1+S_{GD}} \left(\frac{L'_{do}-\ell_a^2}{L_{ADO}} \right)$	-0.35
x_{xd}	$x_{xdo} - \frac{S_{GD}L_{ADO}}{1+S_{GD}} \frac{d x_{xd}}{d L_{AD}}$	-27. *
L_q	$L_{qo} - \frac{S_{GQ}L_{AQO}}{1+S_{GQ}}$	-20.7 *
L''_q	$L''_{qo} - \frac{S_{GQ}L_{AQO}}{1+S_{GQ}} \left(\frac{\ell_{kq}}{\ell_{kq}+L_{AQO}} \right)$	-0.65
T'_{do}	$T'_{doo} - \frac{S_{GD}L_{ADO}}{(1+S_{GD})r_F}$	-20.3 *
T''_{do}	$T''_{doo} - \frac{S_{GD}L_{ADO}}{1+S_{GD}} \frac{d T'_{do}}{d L_{AD}}$	-1.39
T'''_{qo}	$T'''_{qoo} - \frac{S_{GQ}L_{AQO}}{1+S_{GQ}} \frac{dT'_{qo}}{d L_{AQ}}$	-0.01
K_1	$K_{10} - \frac{S_{GD}L_{ADO}}{1+S_{GD}} \frac{dK_1}{dL_{AD}}$	3.9

the fully saturated flux linkage model and the simplified E'' model. The results are obviously almost identical.

A statistical analysis of the simplified E'' model is given in Appendix E. The errors analyzed compared favorably with those of the fully saturated E'' model.

2.6 Conclusions

Three forms of simulation model have been shown to provide almost identical results when modified to include the effect of saturation. Those are:

Model A Flux Linkage Model, fully saturated

Model B E'' Model, fully saturated

Model D E'' Model, with simplified saturation

The usual industry practice is to use some form of Model D, saturating only inductances. Our analysis shows that certain gains as well as T'_{d0} should also be treated for the effect of saturation.

The flux linkage model should be examined further for its suitability as a digital model for stability. This model is simpler than models of the E'' type and are easier to saturate. The time constants are really constant for this model and the number of gain parameters is small. We recommend this model for serious considerations in the future.

3.0 EPRI STABILITY PROGRAM SIMULATION

3.1 Digital Model of the Wind Turbine Generator

The purpose of this task is to provide a digital implementation of the Purdue MOD-2 Wind Turbine Generator Model for use on the EPRI Transient Mid-Term Stability Program (ETMSTAB). The Purdue Model is well documented in published references [4-6] and private communications [7]. A block diagram summarizing the component models and their interconnection, modified for digital simulation, is shown in Figure 3.1. The blade dynamics are approximated by the nonlinear functions

$$\gamma = \frac{V_W}{\omega_B} \quad (3.1)$$

$$C_p = \frac{1}{2} (\gamma - 0.022\beta^2 - 5.6)e^{-0.17\gamma} \quad (3.2)$$

$$P_W = \frac{1}{2} \rho A C_p V_W^3$$
$$\approx \frac{1}{2} \rho A \omega_{B0} C_p \gamma V_W^2 \quad (3.3)$$

where V_W = wind velocity in mi/h
 ω_B = blade angular velocity in mech rad/s
 γ = tip speed ratio in (mi/h)/(rad/s)
 β = blade pitch angle, degrees
 C_p = power coefficient (dimensionless)
 ρ = air density in lbf/ft³
 A = blade impact area in ft²

Figure 3.1 Block Diagram of the Digital MOD-2 Model

Function (3.2) was not available in the ETMSTAB modular modeling package and was therefore constructed as a special module.

The Purdue Modelers devised the approximate expression (3.2) for the power coefficient C_p as a nonlinear function of blade pitch angle, β , and tip speed ratio, γ . This function is shown in Figure 3.2. In the digital simulation, it was found convenient to multiply this function by the forward loop gain T_{WCON} equal to 6.151×10^{-6} . This constant converts the turbine output torque in joules to per unit, normalized on the ETMSTAB base of 100 MVA, with all forward loop constants collected into the one value, as noted in Figure 3.1.

The blade output power as a function of wind velocity is shown in Figure 3.3, which is a plot of the P_W vs V_W of Figure 3.1 at rated blade speed and for various pitch angles. It is noted that these characteristic curves level off at wind velocities of 45-50 mi/h.

The blade torque-speed characteristic is of interest in power generation, since this characteristic works against the torque-speed characteristic of the load to determine frequency regulation or governing. The MOD-2 torque-speed characteristic varies with wind velocity, with two characteristic curves given in Figure 3.4. (Note that the two plots of Figure 3.4 have different vertical scales.) We are interested in these plots only in the neighborhood of rated speed (1.848 rad/s). In this region, the torque characteristic is nearly flat, with a small negative slope.

The turbine power vs. speed characteristic is shown in Figure 3.5, where again we focus our attention in the region near 1.848 rad/s. Here the slope is observed to be definitely positive for small blade angles and corresponding high power output. Our simulation of the wind turbine

Figure 3.2 **Power Coefficient as a Function of Gamma**
for Pitch Angles of (top to bottom) 0-36 degrees
in 4 degree increments

Figure 3.3 Wind Turbine Output Power vs Wind Velocity at
Rated Blade Angular Velocity, Pitch Angles
(top to bottom) of 0, 4, 8, 12, 16 and 20 degrees

Figure 3.4 Wind Turbine Torque-Speed Characteristic,
Pitch Angles of 0-36 in 4 degree increments

Figure 3.5 Wind Turbine Power-Speed Characteristic,
Pitch Angles of 0-36 in 4 degree increments

system verified that the open-loop system is marginally unstable for a base wind of 35 mi/h and a scheduled power of 2.55 MW. This point is just barely in the positive slope region.

The pitch control system shown in Figure 3.1, provides integral control of errors in hub speed or generated power, with a notch filter introduced to reduce oscillations of twice the rotational frequency, arising from wind shear phenomena, blade teetering and nacelle yaw [17]. Appropriate limiting of both pitch angle and rate-of-change are incorporated. A mode switch is devised to remove the pitch angle control when the average wind speed is below a nominal cut-off velocity. All the pitch control components, except the mode switch, are simulated using modeling modules normally available in ETMSTAB. The mode switch module is constructed according to the prescribed logic, and is added to the modeling package.

The shaft dynamics model is a straightforward implementation of a linear rotating shaft with three masses, corresponding to the blade, hub, and generator shafts.

All the foregoing model components are discussed in greater detail in Section 3.3.

3.2 Wind Model

The wind model is one feature that is unique to the wind turbine-generator system and is not required for other generator systems in the stability program. A model is required that can properly simulate the spatial effect of wind behavior, including gusting, rapid (ramp) changes, and background noise. Obviously no wind model is available in existing stability programs and must be created as a special modeling module.

The wind model chosen for this simulation is a four-component model, shown graphically in Figure 3.6, and defined by the equation

$$V_W = V_{WB} + V_{WG} + V_{WR} + V_{WN} \quad (3.4)$$

where

V_{WB} = base wind velocity, mi/h

V_{WG} = gust wind component, mi/h

V_{WR} = ramp wind component, mi/h

V_{WN} = noise wind component, mi/h

These four components provide a reasonable flexibility for the study of one or a group of wind generators.

The base wind velocity component is described by the equation

$$V_{WB} = K_B \quad \text{mi/h} \quad (3.5)$$

where K_B is a constant. This component is always assumed to be present in studies where the wind generator is required to be in service.

The gust wind velocity component is described by the equation

$$V_{WG} = \begin{cases} 0 & t < T_{1G} \\ V_{COS} & T_{1G} < t < T_{1G} + T_G \quad \text{mi/h} \\ 0 & t > T_{1G} + T_G \end{cases} \quad (3.6)$$

where

$$V_{COS} = (MAXG/2) \{1 - \cos 2\pi[(t/T_G) - (T_{1G}/T_G)]\}$$

T_G = gust period in s

T_{1G} = gust starting time in s

$MAXG$ = gust peak in mi/h

t = time in s

WIND MODEL

Figure 3.6 Block Diagram of Wind Model

This is the usual 1-cosine gust used in wind studies by others [18], and is considered an essential component of wind velocity for dynamic studies.

The ramp wind velocity component is described by the equation

$$V_{WR} = \begin{cases} 0 & t < T_{1R} \\ V_{ramp} & T_{1R} < t < T_{2R} \text{ mi/h} \\ 0 & t > T_{2R} \end{cases} \quad (3.7)$$

where

$$V_{ramp} = MAXR[1-(t-T_{2R})/(T_{1R}-T_{2R})] \text{ mi/h}$$

$$MAXR = \text{ramp maximum in mi/h}$$

$$T_{1R} = \text{ramp start time in s}$$

$$T_{2R} = \text{ramp max time in s}$$

and where $T_{2R} > T_{1R}$. This functions may be used to approximate a step change, by setting T_{2R} only slightly greater than T_{1R} , or a slowly increasing wind velocity to study ramp tracking. For negative values of $MAXR$, ramps of negative slopes could be studied.

The final wind velocity component is the random noise component, where we define

$$V_{WN} = 2 \sum_{i=1}^N [S_V(\omega_i)\Delta\omega]^{1/2} \cos(\omega_i t + \phi_i), \quad t < 0 \quad (3.8)$$

where

$$\omega_i = (i-1/2)\Delta\omega$$

ϕ_i = a random variable with uniform probability density on the interval 0 to 2π

and the function $S_V(\omega_i)$ is the spectral density function defined by Vaicaitis, et al [19] by the equation

$$S_V(\omega_i) = \frac{2K_N F^2 |\omega_i|}{\pi^2 [1 + (F\omega_i/\mu\pi)^2]^{4/3}} \quad (3.9)$$

where K_N = surface drag coefficient = 0.004

F = turbulence scale, ft = 2000

μ = mean speed of wind at reference height, ft/s
 = 29.33 (30 mi/h)

Various studies have shown that values of $N = 50$ and $\Delta\omega = 0.5-2.0$ rad/s provide results of excellent accuracy.

Simulation results for the wind model are shown in Figures 3.7 and 3.8. Figure 3.7 shows a wind condition with a base component V_{WB} of 30 mi/h (44 ft/s) with ramp and gust components superimposed in (a) and (b) respectively. In Figure 3.7(a) the ramp begins at 10s and ends at 15s with $MAXR = 10$ mi/h (14.67 ft/s). In Figure 3.7(b) the gust component begins at 10s and ends at 15s ($T_G = 5$ s) with $MAXG = 10$ mi/h (14.67ft/s).

Figure 3.8 shows some typical results of the wind model simulation that incorporate random noise. The top figure (a) shows a base wind of 30 mi/h (44 ft/s) with the random component superimposed. The bottom figure (b) shows base, ramp, gust components, and random noise. In each case the random noise spectrum was computed with $\Delta\omega = 0.5$. Similar plots are obtained with $\Delta\omega = 2.0$.

Statistics computed for the random components for $\Delta\omega = 2.0$ are given in Table 3.1. These statistics are typical of those observed in many runs and show a standard deviation of 2.28 ft/s (1.56 mi/h).

Figure 3.7 Wind Model Simulation with $V_{WB} = 30$ mi/h (44 ft/s)

Figure 3.8 Wind Model Simulation with $V_{WB} = 30$ mi/h (44 ft/s)

Similar results were obtained with a range of $\Delta\omega$ from 0.5 to 2.0, using $N = 50$. Figure 3.9 shows a histogram of the random noise components, taken over 125 samples.

Table 3.1 Statistics of Random Noise Component of Wind

Computed for $N = 50$, $\Delta\omega = 2.0$

BASIC STATISTICS

VARIABLE	# OBSERVATIONS	# MISS. VALUES	SUM	MEAN
Vw in ft/s	126	0	-.72884	-.00578

VARIABLE	VARIANCE	STANDARD DEV.	COEF OF SKEWNESS	COEF OF KURTOSIS
Vw in ft/s	5.21165	2.28290	.00857	-.51996

VARIABLE	COEF VARIATION	STANDARD ERROR OF THE MEAN	90% CONFIDENCE LOWER LIMIT	INTERVAL ON MEAN UPPER LIMIT
Vw in ft/s	39466.34613	.20338	-.34288	.33131

ORDER STATISTICS

VARIABLE	MAXIMUM	MINIMUM	RANGE	MIDRANGE
Vw in ft/s	5.50392	-5.18974	10.69365	.15709

3.3 Modular Model for Digital Simulation

Figure 3.1 shows the block diagram of the wind turbine-generator system, modified to meet the modular modeling structures of the stability program ETMSTAB, shown in Figure 1.2. The wind turbine model is also modified to meet restrictions imposed by parameter limitations in ETMSTAB.

Figure 3.9 Histogram of Random Noise Component with
 $\Delta\omega = 2.0$ rad/s.

One restriction of the digital program is the scaling of variables. All computation assumes models to be normalized to a 100 MVA base, with speeds computed in radians per second and time in seconds. This requires a normalization of the turbine generator output P_W to a 100 MVA base. Feedback from the system is similarly normalized. Major modeling accommodations are discussed below. Reference is to Figure 3.1.

The wind model was constructed by adding a special function module to provide V_W in mi/h given the parameters of the four wind components. This special module provided an input to the γ -block, which is represented by a module available in the program.

The blade dynamics model, shown in Figure 3.1, is modified to incorporate all constants into one parameter T_{WCON} . This parameter also normalizes the output P_W to a per unit value. In doing this, the intermediate variable C_p is modified by a constant scale factor to a new variable $\hat{C}_p$. A special model module is then constructed to compute

$$\hat{C}_p = \frac{T_{WCON}}{2} (\gamma - 0.022\beta^2 - 5.6)e^{-0.17\gamma} \quad (3.10)$$

Other model requiremens are met by use of standard modeling modules, provided by the program, with the sole exception of the mode switch. This function is described mathematically by the equation

$$x = \begin{cases} 0 & \text{if } U_2 \leq V_c \\ U_1 & \text{if } U_2 > V_c \end{cases} \quad (3.11)$$

where

x = output

U₁ = input 1 (from speed and power error)

U₂ = input 2 (from average V_W) = V_{WB} + V_{WG} + V_{WR}

V_c = VWCUT

The parameter VWCUT is the pitch control cutoff wind velocity and must be input as a control parameter. The equation (3.11) is also constructed as a special modeling module.

The notch filter requires special handling as a digital filter design, but this is accomplished using standard model modules. The program implements a technique described by Cadzow [20]. The particular filter required here is a special case of the function

$$x = \frac{s^2 + a s + b}{s^2 + c s + d} u \quad (3.12)$$

where, in our case, $c = 10a$ and $b = d$. This permits a simplification of Cadzow's filter to the form shown in Figure 3.10, where we let

$$AFILT = a - 0 = -\phi a$$

$$BFILT = -b$$

$$CFILT = -c \quad (3.13)$$

These three parameters are input parameters to the program.

The program has a basic limitation of 22 parameters that can be specified for a governor-turbine model. These parameters, and their values, are shown in Table 3.2. All other parameters required for the simulation, 14 in all, were incorporated as parameters for special modeling modules. These parameters are given in Table 3.3.

Figure 3.10 Digital Implementation of the Notch Filter

Table 3.2 Wind Governor-Turbine Parameters

<u>No</u>	<u>Parameter</u>	<u>Value</u>	<u>Units</u>
1	KS	0.00487	pu
2	K1	370.0	deg/(rad/s)
3	K2	15.0	deg/puMW
4	K3	4.0	deg-s/puMW
5	VWCUT	28.0	mi/h
6	AILT	-0.338	pu
7	BFILT	-13.5	pu
8	CFILT	-0.375	pu
9	K4	6.28	pu
10	PZ	—	pu
11	RLMIN	-10.0	deg/s
12	RLMAX	10.0	deg/s
13	BMIN	0.0	deg
14	BMAX	34.0	deg
15	DB	6.782E-5	pu/(rad/s)
16	JB	4.852E-1	s ²
17	KBH	1.275E-1	pu/rad
18	DBH	4.340E-1	pu/(rad/s)
19	DH	8.206E-5	pu/(rad/s)
20	JH	1.296E-2	s ²
21	KGH	2.102E-1	pu/rad
22	EGH	1.356E-2	pu/(rad/s)

Table 3.3 Special Model Parameters

<u>Module</u>	<u>Parameter</u>	<u>Value</u>	<u>Units</u>
Speed Ref	ω_{BO}	1.8379	rad/s
Wind	KB	user selected	mi/h
"	MAXG	"	mi/h
"	T1G	"	s
"	TG	"	s
"	MAXR	"	mi/h
"	T1R	"	s
"	T2R	"	s
"	KN	"	mi/h
"	MU	"	ft/s
"	F	"	ft
"	DELW	"	rad/s
Blade	TWCON	6.5155E-6	pu·h/mi·s
Rating	PMAWWT	3.125	MVA

3.4 ETMSTAB Simulation of the Wind Generator

Computer simulations of the wind turbine were run using the familiar 9 bus test system shown in Figures 3.11. The wind generator was added to bus 3 and scheduled to generate 2% of the schedule 85 MW, or 1.7 MW. The steam unit is therefore backed off to 83.3 MW. A large number of test runs were made in this configuration to check out the various wind model features.

Table 3.4 summarizes the computer runs that were plotted for this report. In all cases where a random noise component is present, indicated by an X in Table 3.4, the noise parameters were $\Delta\omega = 2.0$, $F = 2000$, $K_N = 0.004$.

Results are shown in Figures 3.12 - 3.21. In each figure, three results are plotted; the wind velocity, the blade pitch angle, and the turbine mechanical power. Comments on these simulated results follow.

Table 3.4 Summary of Computer Runs of the
Nine Bus Test System. All Wind Values in mi/h.

Run	Base	Ramp	Gust	Noise	Figure
WT01	30	5	-	-	3.12
WT02	30	-	5	-	3.13
WT03	30	-	-	X	3.14
WT04	25	5	-	-	3.15
WT05	25	-	5	-	3.16
WT06	25	-	-	X	3.17
WT07	30	5	-	X	3.18
WT08	30	0	5	X	3.19
WT09	30	-5	-	X	3.20
WT10	30	-	-5	X	3.21

Runs WT01 - 03, shown in Figures 3.12-14, illustrate the effect of each wind component. Many variations of these runs were tried, from very short gusts and steep ramps to slower variations. Various noise parameters were also tested. All runs verify that the model performs as dictated by the theory.

Figure 3.11 Nine Bus Test System; Top: Impedance Diagram,
Bottom: Initial Conditions

Figure 3.12 Wind Turbine Performance for Case WT01

Figure 3.13 Wind Turbine Performance for Case WT02

Figure 3.14 Wind Turbine Performance for Case WT03

Figure 3.15 Wind Turbine Performance for Case WT04

Figure 3.16 Wind Turbine Performance for Case WT05

Figure 3.17 Wind Turbine Performance for Case WT06

Figure 3.18 Wind Turbine Performance for Case WT07

Figure 3.19 Wind Turbine Performance for Case WT08

Figure 3.20 Wind Turbine Performance for Case WT09

Figure 3.21 Wind Turbine Performance for Case WT10

Runs WT04 - 06, shown in Figures 3.15-17, and using a base wind of 25 mi/h, illustrate a basic problem in the simulations. The stability program is initialized from a power flow calculation, in our case that given in Figure 3.11 with the wind generator set initially to 1.7 MW output power as a contribution to the generated power at bus 3. Now 25 mi/h is below the cutoff wind velocity value of 28 mi/h used as a threshold value for pitch control. Since $V_W < 28$, the program resets the control to zero as soon as the dynamic simulation begins. The pitch angle cannot be set initially to zero because 25 mi/h at zero pitch gives a turbine output power, from Figure 3.3, of about 2.2 MW. But this output power would violate the initial conditions. Since it is not practical to require a new power flow solution to match the zero pitch power, the stability program computes a pitch angle that corresponds to the given wind and power setting. The dynamic simulation program promptly resets the pitch angle to zero as long as the average wind velocity is below 28 mi/h.

To test the wind velocity for possible cutoff of pitch control, an average test wind velocity is used, defined as

$$V_{TEST} = V_{WB} + V_{WG} + V_{WR} \quad (3.14)$$

The noise component was not included since it tends to turn the controller on and off continually. The test velocity (3.14) provides an average wind function that is more typical of the average that would be observed in the field.

Simulation runs WT07-10, shown in Figures 3.18-21, show the effect of positive and negative gusts and ramps that are modified by noise.

4.0 CONCLUSIONS

The MOD-2 wind turbine generator model developed by Purdue University has been adapted for digital transient stability simulation using the advanced EPRI stability program ETMSTAB. There are certain problems in modeling the wind turbine for digital simulation, but none that are beyond resolution. The EPRI program was capable of modeling most functions directly, and the remaining special functions were added by coding modifications. Seven subroutines required modification, with most of the changes in four subroutines. One subroutine was rewritten in its entirety. The results were satisfactory in every respect.

The production version of ETMSTAB will have features that will be of considerable value for the study of wind turbine dynamics. Where our simulation was limited to a single wind generator, the utility user will often want to study a group of wind machines. This suggests two possible modes of oscillation: 1. where the entire group of wind machines swings together, or 2. where substantial intermachine oscillation takes place within the group. ETMSTAB will have the capability of forming a dynamic equivalent of the entire wind group in the former case, or of studying the intermachine oscillation of the latter.

Considerable effort was spent on synchronous machine modeling as a part of this project. It is believed that additional work may be warranted to develop models of machine saturation that are accurate and easy to apply.

It was not the purpose of this study to develop a wind turbine model, but only to apply the model previously developed by Purdue University. Additional effort should be initiated to develop a generic wind turbine model, normalized to the size of the generator, and that can be used for a variety of different wind machines. Wind turbines will not receive serious consideration from power system planners until such models are available.

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APPENDIX A

Simulation Results with Complete Saturation

for a

10% Step Change in T_m

Figure A.1.a T_m vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.1.b T_m vs time in seconds, E'' model (b),
step change in T_m , saturated (*) and unsaturated response

Figure A.2.a E_{FD} vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.2.b E_{FD} vs time in seconds, E'' model (b),
step change in T_m , saturated (*) and unsaturated response

Figure A.3.a V_t vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.3.b V_t vs time in seconds, E'' model (b),
step change in T_m , saturated (*) and unsaturated response

Figure A.4.a I_a vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.4.b I_a vs time in seconds, E'' model (b),
step change in T_m , saturated (*) and unsaturated response

Figure A.5.a T_e vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.5.b T_e vs time in seconds, E'' model (b),

step change in T_m , saturated (*) and unsaturated response

Figure A.6.a $\Delta\omega$ vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.6.b $\Delta\omega$ vs time in seconds, E'' model (b),
 step change in T_m , saturated (*) and unsaturated response

Figure A.7.a δ vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.7.b δ vs time in seconds, E'' model (b),
step change in T_m , saturated (*) and unsaturated response

Figure A.8.a S_{gd} vs time in seconds, flux linkage model (a),
 step change in T_m , saturated (*) and unsaturated response

Figure A.8.b S_{gd} vs time in seconds, E'' model (b),
step change in T_m , saturated (*) and unsaturated response

Figure A.9.a ψ_{AD} vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.9.b ψ_{AD} vs time in seconds, E'' model (b),
 step change in T_m , saturated (*) and unsaturated response

Figure A.10.a Ψ_d vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.10.b ψ_d vs time in seconds, E'' model (b),

step change in T_m , saturated (*) and unsaturated response

Figure A.11.a ψ_F vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.11.b ψ_F vs time in seconds, E'' model (b),
step change in T_m , saturated (*) and unsaturated response

Figure A.12.a Ψ_{kd} vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.12.b ψ_{kd} vs time in seconds, E'' model (b),

step change in T_m , saturated (*) and unsaturated response

Figure A.13.a I_d vs time in seconds, flux linkage model (a),
step change in I_m , saturated (*) and unsaturated response

Figure A.13.b I_d vs time in seconds, E'' model (b),
step change in T_m , saturated (*) and unsaturated response

Figure A.14.a I_f vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.14.b I_f vs time in seconds, E'' model (b),
step change in T_m , saturated (*) and unsaturated response

Figure A.15.a I_{kd} vs time in seconds, E'' model (b),

step change in T_m , saturated (*) and unsaturated response

Figure A.15.b I_{kd} vs time in seconds, E'' model (b),
step change in T_m , saturated (*) and unsaturated response

Figure A.16.a S_{gp} vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.16.b S_{gp} vs time in seconds, E'' model (b),
 step change in T_m , saturated (*) and unsaturated response

Figure A.17.a ψ_{AQ} vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.17.b ψ_{AQ} vs time in seconds, E'' model (b),

step change in T_m , saturated (*) and unsaturated response

Figure A.18.a ψ_q vs time in seconds, flux linkage model (a),
 step change in T_m , saturated (*) and unsaturated response

Figure A.18.b ψ_q vs time in seconds, E'' model (b),
step change in T_m , saturated (*) and unsaturated response

Figure A.19.a ψ_{kq} vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.19.b k_q vs time in seconds, E'' model (b),
 step change in T_m , saturated (*) and unsaturated response.

Figure A.20.a I_q vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.20.b I_q vs time in seconds, E'' model (b),
step change in T_m , saturated (*) and unsaturated response

Figure A.21.a I_{kq} vs time in seconds, flux linkage model (a),
step change in T_m , saturated (*) and unsaturated response

Figure A.21.b I_{kq} vs time in seconds, E'' model (b),
 step change in T_m , saturated (*) and unsaturated response

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APPENDIX B

Simulation Results with Complete Saturation

for a

5% Step Change in E_{FD}

Figure B.1.a T_m vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.1.b T_m vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

Figure B.2.a E_{FD} vs time in seconds, flux linkage model (a),
step change in E_{FD} , saturated (*) and unsaturated response

Figure B.2.b E_{FD} vs time in seconds, E'' model (b),
step change in E_{FD} , saturated (*) and unsaturated response

Figure B.3.a V_t vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.3.b V_t vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

Figure B.4.a I_a vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.4.b I_a vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

Figure B.5.a T_e vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.5.b T_e vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

Figure B.6.a $\Delta\omega$ vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.6.b $\Delta\omega$ vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

Figure B.7.a δ vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.7.b δ vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

Figure B.8.a S_{gd} vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.8.b S_{gd} vs time in seconds, E'' model (b),
step change in EFD; saturated (*) and unsaturated response

Figure B.9.a ψ_{AD} vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.9.b ψ_{AD} vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

Figure B.10.a Ψ_d vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.10.b ψ_d vs time in seconds, E'' model (b),

step change in EFD, saturated (*) and unsaturated response

Figure B.11.a ψ_F vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.11.b ψ_F vs time in seconds, E'' model (b),

step change in EFD, saturated (*) and unsaturated response

Figure B.12.a ψ_{kd} vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.12.b ψ_{kd} vs time in seconds, E'' model (b),
 step change in EFD, saturated (*) and unsaturated response

Figure B.13.a I_d vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.13.b I_d vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

Figure B.14.a I_f vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.14.b I_f vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

Figure B.15.a I_{kd} vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

Figure B.15.b I_{kd} vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

Figure B.16.a S_{gp} vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

S_{gp}

S_{gp}

Figure B.16.b S_{gp} vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

Figure B.17.a ψ_{AQ} vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.17.b ψ_{AQ} vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

Figure B.18.a ψ_q vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.18.b ψ_q vs time in seconds, E'' model (b),

step change in EFD, saturated (*) and unsaturated response

Figure B.19.a ψ_{kq} vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.19.b ψ_{kq} vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

Figure B.20.a I_q vs time in seconds, flux linkage model (a).
step change in EFD, saturated (*) and unsaturated response

Figure B.20.b I_q vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

Figure B.21.a I_{kq} vs time in seconds, flux linkage model (a),
step change in EFD, saturated (*) and unsaturated response

Figure B.21.b I_{kq} vs time in seconds, E'' model (b),
step change in EFD, saturated (*) and unsaturated response

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APPENDIX C

Simulation Results for the Flux Linkage Model

Comparing Full Saturation
to
Partial Saturation
with
Constant L_{MD} and L_{MQ}

Figure C.1 T_m vs time in seconds, Simplified Flux Linkage Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.2 E_{FD} vs time in seconds, Simplified Flux Linkage Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.3 V_t vs time in seconds, Simplified Flux Linkage Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.4 I_a vs time in seconds, Simplified Flux Linkage Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.5 T_e vs time in seconds, Simplified Flux Linkage Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.6 $\Delta\omega$ vs time in seconds, Simplified Flux Linkage Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.7 δ vs time in seconds, Simplified Flux Linkage Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.8 S_{GD} vs time in seconds, Simplified Flux Linkage Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.9 ψ_{AD} vs time in seconds, Simplified Flux Linkage Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.10 ψ_d vs time in seconds, Simplified Flux Linkage Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.11 ψ_F vs time in seconds, Simplified Flux Linkage Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.12 ψ_{kd} vs time in seconds, Simplified Flux Linkage Model,

Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.13 I_d vs time in seconds, Simplified Flux Linkage Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.14 I_f vs time in seconds, Simplified Flux Linkage Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.15 I_{kd} vs time in seconds, Simplified Flux Linkage Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.16 S_{Gq} vs time in seconds, Simplified Flux Linkage Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.17 ψ_{AQ} vs time in seconds, Simplified Flux Linkage Model,

Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.18 ψ_q vs time in seconds, Simplified Flux Linkage Model,

Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.19 ψ_{kq} vs time in seconds, Simplified Flux Linkage Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.20 I_q vs time in seconds, Simplified Flux Linkage Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure C.21 I_{kq} vs time in seconds, Simplified Flux Linkage Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

APPENDIX D

Simulation Results Comparing Flux Linkage and E'' Models with the E'' Model only Partially Saturated

Figure D.1 T_m vs time in seconds, Simplified E'' Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.2 E_{FD} vs time in seconds, Simplified E'' Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.3 V_t vs time in seconds, Simplified E'' Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.4 I_a vs time in seconds, Simplified E'' Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.5 T_e vs time in seconds, Simplified E'' Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.6 $\Delta\omega$ vs time in seconds, Simplified E'' Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

DI in Degree

DI in Degree

Figure D.7 δ vs time in seconds, Simplified E'' Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.8 S_{GD} vs time in seconds, Simplified E'' Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.9 ψ_{AD} vs time in seconds, Simplified E'' Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.10 ψ_d vs time in seconds, Simplified E'' Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.11 ψ_F vs time in seconds, Simplified E'' Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.12 ψ_{kd} vs time in seconds, Simplified E'' Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.13 I_d vs time in seconds, Simplified E'' Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.14 I_F vs time in seconds, Simplified E'' Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.15 I_{kd} vs time in seconds, Simplified E'' Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.16 S_{GQ} vs time in seconds, Simplified E'' Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.17 ψ_{AQ} vs time in seconds, Simplified E'' Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.18 ψ_q vs time in seconds, Simplified E'' Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FU}

Figure D.19 ψ_{kq} vs time in seconds, Simplified E'' Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.20 I_q vs time in seconds, Simplified E'' Model,
 Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

Figure D.21 I_{kq} vs time in seconds, Simplified E'' Model,
Top: 10% Change in T_m , Bottom: 5% Change in E_{FD}

APPENDIX E

Statistical Analysis of Differences

in

Simulated Results

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STATISTICAL ANALYSIS OF DIFFERENCES IN SIMULATION RESULTS

The graphical statistical analyses of results presented here are of two types: histograms and normal probability plots. All results are for differences between time domain simulations. Simulation results are identified by letter code, using the coding scheme of Table E.1. Data for analysis is provided by subtracting, point by point, the time domain simulation results, with 126 such points retained for analysis.

Comparisons are provided for ten cases, as shown in Table E.2. For each case listed, two statistical analysis graphs are provided: a histogram and a normal probability plot.

The histogram plots the relative frequency of eight classes vs the class intervals. Class frequency is determined by summing the total number of measurements in a given class or cell. Relative frequency is this class frequency divided by 126, the total population. Each histogram is overlaid by a best fit of the data to a normal distribution.

The normal probability plot is the second graphical aid provided. These graphs show the actual errors (differences) plotted vs the percent of values that fall below a given abscissa value. If this plot is a straight line then the data comes from a normal distribution.

General Comments on Statistical Graphs

The statistical difference between the flux linkage and E'' models, for the unsaturated case, is given in Figure E1. The differences are generally very small and are non-gaussian. Nearly all errors are clustered around zero, and are small.

Table E.1 Coding of Simulation Runs

<u>Code</u>	<u>Model</u>	<u>Saturation</u>
EA	Flux Linkage	Unsaturated Case
EB	E''	Unsaturated Case
A	Flux Linkage	Complete: L_{AD} and L_{AQ}
B	E''	Complete: All L's, T's, and K's
C	Flux Linkage	Only ψ_{AD} and ψ_{AQ} , constant L's
D	E''	Only L_d , x_{xd} , K_d , L_q , and T'_{do}

Table E.2 Comparison Sets for Statistical Analysis

<u>Code</u>	<u>Designation</u>	<u>Disturbance</u>	<u>Table</u>	<u>Figure</u>
EAEBTC	EA-EB	T_m	E3 a	E1 a
EAEBVC	EA-EB	E_{FD}	E3b	E1b
ABTC	A-B	T_m	E4 a	E2 a
ABVC	A-B	E_{FD}	E4b	E2b
AEATC	A-EA	T_m	E5 a	E3 a
AEAVC	A-EA	E_{FD}	E5b	E3b
ACTC	A-C	T_m	E6 a	E4 a
ACVC	A-C	E_{FD}	E6b	E4b
ADTC	A-D	T_m	E7 a	E5 a
ADVC	A-D	E_{FD}	E7b	E5b

enough to be considered negligible. A statistical summary of errors in all variables is given in Tables E3a and E3b, for T_m and E_{FD} disturbances, respectively. Note that the standard deviation in all variables is very small and considered well within acceptable tolerance.

The statistical errors between fully saturated flux linkage and E'' fully saturated models (A and B, respectfully) are given in Figure E2 and in Tables E4a and E4b. These errors are in about the same range as for the unsaturated case and show only slightly larger standard deviation. The results are clearly from a normal distribution. The accuracy is clearly acceptable, or, stated another way, the models are statistically equivalent.

A comparison of the saturated flux linkage model and the same model with no saturation (A-EA) is shown in Figure E3 and in Tables E5a and E5b. The errors here are much greater and are generally not gaussian. Some of the results are surprising. Certain variables, such as T_e , are affected very little by saturation and show very little change in standard deviation or standard error. Other variables are greatly affected by saturation, such as torque angle, and therefore show much greater error. These statistics are displayed simply to show an approximate worst case in saturation analysis, and will be used only for comparison. The effect of saturation is also clearly displayed in the time domain plots of Appendices A-D.

Figure E4 and Tables E6 compare the saturated flux linkage model (A) against the same model with simplified saturation (C). These results are disappointing and indicate the need for a different approach. The statistics here are only slightly better than the comparison against an unsaturated model.

The final comparison is for the E'' model with saturation applied only to the five parameters that are most sensitive to change in L_{AD} and L_{AQ} . These results are shown in Figure E5 and Table E7. These statistics indicate that this model (D) performs almost exactly the same as the more detailed saturation model (B). Errors are almost identical to the more detailed case and are very small. Most errors plotted are nearly gaussian.

PERCENT UNDER
NORMAL PROBABILITY PLOT

Figure E.1.a.1 Statistical Plots of EA-EB for a T_m Disturbance,

Data for T_e

Figure E.1.a.2 Statistical Plots of EA-EB for a T_m Disturbance,

Data for $\Delta\omega$

DI

Figure E.1.a.3 Statistical Plots of EA-EB for a T_m Disturbance,

Data for 8

Figure E.1.a.4 Statistical Plots of EA-EB for a T_m Disturbance,
Data for V_t

Te

Figure E.1.b.1 Statistical Plots of EA-EB for a E_{FD} Disturbance,

Data for T_e

Dom

PERCENT UNDER
NORMAL PROBABILITY PLOT

Figure E.1.b.2 Statistical Plots of EA-EB for a E_{FD} Disturbance,

Data for $\Delta\omega$

Figure E.1.b.3 Statistical Plots of EA-EB for a E_{PD} Disturbance,

Data for 8

PERCENT UNDER
NORMAL PROBABILITY PLOT

Figure E.1.b.4 Statistical Plots of EA-EB for a E_{FD} Disturbance,

Data for V_t

Table E.3a Statistical Analysis of the Difference between Flux

Linkage and E'' Models, Unsaturated Case,

Step Change in T_m

VARIABLE	VARIANCE	STANDARD DEV.	COEF OF SKEWNESS	COEF OF KURTOSIS
Vt	.000000	.000047	.14607	-.51540
Te	.000001	.000006	.63804	1.85402
Dom	.000004	.000095	.32791	2.43475
Dl	.01308	.11436	.72475	1.87038
Wad	.000000	.00109	-.59785	.23736
Wd	.000000	.00199	-.57064	.70818
Wf	.000000	.00158	-.46070	-.61932
Wkd	.000000	.00059	-.81037	1.09463
Waq	.000000	.00086	1.05424	2.17038
Wq	.000000	.00095	1.05222	2.19610
Wkq	.000000	.00086	1.04856	2.14446

VARIABLE	COEF VARIATION	STANDARD ERROR OF THE MEAN	90 % CONFIDENCE INTERVAL ON MEAN	
			LOWER LIMIT	UPPER LIMIT
Vt	1068.59893	.00004	-.00011	.00003
Te	709.86829	.00027	-.00002	.00008
Dom	20343.95052	.00053	-.00005	.00009
Dl	408.46946	.01019	.01111	.04489
Wad	166.30216	.00010	-.00002	-.00050
Wd	256.96945	.00018	-.00107	-.00048
Wf	151.28775	.00014	-.00128	-.00081
Wkd	139.02282	.00005	-.00051	-.00034
Waq	311.04086	.00008	.00015	.00040
Wq	316.18722	.00008	.00016	.00044
Wkq	311.39233	.00008	.00015	.00040

ORDER STATISTICS

VARIABLE	MAXIMUM	MINIMUM	RANGE	MIDRANGE
Vt	.00103	-.00100	.00203	.00002
Te	.00953	.00679	.01632	.00137
Dom	.02082	-.01536	.03619	.00273
Dl	.37020	-.23530	.60550	.06745
Wad	.00151	-.00353	.00504	-.00101
Wd	.00349	-.00620	.00969	-.00136
Wf	.00174	-.00476	.00650	.00151
Wkd	.00079	-.00211	.00290	-.00066
Waq	.00301	-.00147	.00448	.00077
Wq	.00335	-.00165	.00500	.00085
Wkq	.00300	-.00147	.00447	.00077

Table E.3b Statistical Analysis of the Difference between Flux

Linkage and E'' Models, Unsaturated Case,

Step Change in E_{FD}

VARIABLE	VARIANCE	STANDARD DEV.	COEF OF SKEWNESS	COEF OF KURTOSIS
Vt	.00000	.00002	-.94907	1.36433
Te	.00000	.00007	-.10304	1.68437
Dom	.00000	.00014	-.64473	1.80521
Dl	.00001	.00384	-.13018	.79189
Wad	.00000	.00015	-1.78006	3.16987
Wd	.00000	.00016	-1.42898	2.50905
Wf	.00000	.00029	-1.76877	3.08014
Wkd	.00000	.00009	-1.98396	3.75206
Waq	.00000	.00004	.26216	.70886
Wq	.00000	.00004	.19889	.88476
Wkq	.00000	.00004	.20117	.67172

VARIABLE	COEF VARIATION	STANDARD ERROR OF THE MEAN	90% CONFIDENCE INTERVAL ON MEAN LOWER LIMIT	UPPER LIMIT
Vt	38.66293	.00000	.00005	.00006
Te	70935.38565	.00001	-.00001	.00001
Dom	1061.87427	.00001	-.00003	.00001
Dl	49.66939	.00034	-.00829	-.00716
Wad	34.32123	.00001	.00043	.00047
Wd	35.85086	.00001	.00042	.00047
Wf	34.37581	.00003	.00079	.00087
Wkd	33.45847	.00001	.00025	.00027
Waq	48.12618	.00000	-.00008	-.00007
Wq	48.20545	.00000	-.00009	-.00007
Wkq	48.67354	.00000	-.00008	-.00007

ORDER STATISTICS

VARIABLE	MAXIMUM	MINIMUM	RANGE	MIDRANGE
Vt	.00010	0.00000	.00010	.00005
Te	.00021	-.00020	.00041	.00001
Dom	.00032	-.00044	.00076	-.00006
Dl	0.00000	-.01740	.01740	-.00870
Wad	.00065	0.00000	.00065	.00033
Wd	.00070	0.00000	.00070	.00035
Wf	.00118	0.00000	.00118	.00059
Wkd	.00037	0.00000	.00037	.00019
Waq	0.00000	-.00016	.00016	-.00008
Wq	.00001	-.00018	.00019	-.00009
Wkq	0.00000	-.00016	.00016	-.00008

T_e

Figure E.2.a.1 Statistical Plots of A-B for a T_m Disturbance,
Data for T_e

Dom

Figure E.2.a.2 Statistical Plots of A-B for a T_m Disturbance,

Data for $\Delta\omega$

DI

Figure E.2.a.3 Statistical Plots of A-B for a T_m Disturbance,
Data for δ

NORMAL PROBABILITY PLOT

Figure E.2.a.4 Statistical Plots of A-B for a T_m Disturbance,

Data for V_t

T_e

NORMAL PROBABILITY PLOT

Figure E.2.b.1 Statistical Plots of A-B for a E_{FD} Disturbance,

Data for T_e

NORMAL PROBABILITY PLOT

Figure E.2.b.2 Statistical Plots of A-B for a E_{FD} Disturbance,

Data for $\Delta\omega$

D1

Figure E.2.b.3 Statistical Plots of A-B for a E_{PD} Disturbance,

Data for δ

V_t

NORMAL PROBABILITY PLOT

Figure E.2.b.4 Statistical Plots of A-B for a E_{FD} Disturbance,

Data for V_t

Table E.4a Statistical Analysis of the Difference between Flux
Linkage and E'' Models, Complete Saturation,
Step Change in T_m

VARIABLE	VARIANCE	STANDARD DEV.	COEF OF SKEWNESS	COEF OF KURTOSIS
Vt	.00000	.00043	-.14242	-1.00825
Te	.00002	.00423	.17241	-.44924
Dom	.00007	.00823	.04381	-.29329
Dl	.02908	.17053	.30152	-.33805
Wad	.00000	.00168	-.50770	-.51773
Wd	.00001	.00285	-.36144	-.43966
Wf	.00000	.00107	-.48853	-.54769
Wkd	.00000	.00125	.71401	-.47850
Waq	.00000	.00138	.40344	-.12501
Wq	.00000	.00153	.40933	-.11928
Wkq	.00000	.00138	.40216	-.12820

VARIABLE	COEF VARIATION	STANDARD ERROR OF THE MEAN	90 % CONFIDENCE INTERVAL ON MEAN LOWER LIMIT	UPPER LIMIT
Vt	75.12954	.00004	.00051	.00064
Te	1401.91844	.00038	-.00032	.00093
Dom	4589.39722	.00073	-.00140	.00104
Dl	364.73900	.01519	-.07194	-.02157
Wad	109.61655	.00015	.00128	.00178
Wd	209.75613	.00025	.00094	.00178
Wf	124.23425	.00018	.00130	.00188
Wkd	73.78671	.00011	.00151	.00188
Waq	251.44652	.00012	-.00075	-.00034
Wq	250.08574	.00014	-.00084	-.00039
Wkq	250.85622	.00012	-.00075	-.00035

ORDER STATISTICS

VARIABLE	MAXIMUM	MINIMUM	RANGE	MIDRANGE
Vt	.00129	-.00032	.00161	.00049
Te	.00997	-.00842	.01839	.00078
Dom	.02075	-.01816	.03891	.00130
Dl	.36400	-.37730	.74130	-.00665
Wad	.00410	-.00253	.00663	.00079
Wd	.00648	-.00550	.01198	.00049
Wf	.00451	-.00317	.00768	.00067
Wkd	.00339	-.00132	.00471	.00104
Waq	.00295	-.00313	.00608	-.00009
Wq	.00330	-.00347	.00677	-.00009
Wkq	.00294	-.00312	.00606	-.00009

Table E.4b Statistical Analysis of the Difference between Flux

Linkage and E'' Models, Complete Saturation,

Step Change in E_{FD}

VARIABLE	VARIANCE	STANDARD DEV.	COEF OF SKEWNESS	COEF OF KURTOSIS
Vt	.00000	.00026	.78307	-.85525
Te	.00000	.00014	-.20205	-.15131
Dom	.00000	.00032	1.06766	.47437
Dl	.00077	.02781	-.78332	-.89179
Wad	.00000	.00089	.65894	-1.07597
Wd	.00000	.00084	.66680	-1.05025
Wf	.00000	.00116	.59965	-1.07326
Wkd	.00000	.00087	.71729	-1.02238
Waq	.00000	.00036	-.75650	-.95121
Wq	.00000	.00040	-.76563	-.93507
Wkq	.00000	.00036	-.74771	-.96861

VARIABLE	COEF VARIATION	STANDARD ERROR OF THE MEAN	90 % CONFIDENCE INTERVAL ON MEAN LOWER LIMIT	UPPER LIMIT
Vt	57.07819	.00002	-.00049	-.00042
Te	11989.30176	.00001	-.00002	.00002
Dom	250.39015	.00003	.00008	.00017
Dl	65.69958	.00248	.03822	.04644
Wad	70.23875	.00008	-.00140	-.00114
Wd	73.10727	.00007	-.00127	-.00102
Wf	85.70405	.00010	-.00152	-.00118
Wkd	61.09423	.00008	-.00155	-.00129
Waq	64.18031	.00003	.00051	.00061
Wq	63.86646	.00004	.00056	.00068
Wkq	64.18548	.00003	.00051	.00061

ORDER STATISTICS

VARIABLE	MAXIMUM	MINIMUM	RANGE	MIDRANGE
Vt	.00008	-.00071	.00079	-.00032
Te	.00030	-.00033	.00063	-.00002
Dom	.00099	-.00031	.00130	.00034
Dl	.07100	-.01150	.08250	.02975
Wad	.00049	-.00216	.00265	.00084
Wd	.00047	-.00199	.00246	-.00076
Wf	.00100	-.00258	.00358	-.00079
Wkd	.00025	-.00224	.00249	-.00100
Waq	.00093	-.00012	.00105	.00041
Wq	.00103	-.00012	.00115	.00046
Wkq	.00093	-.00011	.00104	.00041

T_3

Figure E.3.a.1 Statistical Plots of A-EA for a T_m Disturbance,

Data for T_e

Figure E.3.a.2 Statistical Plots of A-EA for a T_m Disturbance,

Data for $\Delta\omega$

DI

NORMAL PROBABILITY PLOT

Figure E.3.a.3 Statistical Plots of A-EA for a T_m Disturbance,

Data for 6

NORMAL PROBABILITY PLOT

Figure E.3.a.4 Statistical Plots of A-EA for a T_m Disturbance,

Data for V_t

PERCENT UNDER
NORMAL PROBABILITY PLOT

Figure E.3.b.1 Statistical Plots of A-EA for a E_{FD} Disturbance,

Data for T_e

PERCENT UNDER
NORMAL PROBABILITY PLOT

Figure E.3.b.2 Statistical Plots of A-EA for a E_{PD} Disturbance,

Data for $\Delta\omega$

D1

Figure E.3.b.3 Statistical Plots of A-EA for a E_{FD} Disturbance,

Data for δ

NORMAL PROBABILITY PLOT

Figure E.3.b.4 Statistical Plots of A-EA for a E_{FD} Disturbance,

Data for V_t

**Table E.5a Statistical Analysis of the Difference between
the Saturated (A) and Unsaturated (EA) Flux
Linkage Model, Step Change in T_m**

VARIABLE	VARIANCE	STANDARD DEV.	COEF OF SKEWNESS	COEF OF KURTOSIS
Vt	.000000	.00185	.13624	-1.21371
Te	.000001	.00256	.01178	-.95088
Dom	.000002	.00485	-.09121	-.95188
Dl	.05760	.24001	-.44691	-.78879
Wad	.000004	.00639	.13988	-1.15220
Wd	.000004	.00627	.20068	-1.06336
Wf	.000003	.00546	.31947	-1.19476
Wkd	.000004	.00637	.14318	-1.15312
Waq	.000001	.00376	-.41497	-.74488
Wq	.000001	.00303	-.44040	-.74899
Wkq	.000001	.00276	-.41537	-.74388

VARIABLE	COEF VARIATION	STANDARD ERROR OF THE MEAN	90 % CONFIDENCE INTERVAL ON MEAN LOWER LIMIT	UPPER LIMIT
Vt	69.25696	.00016	.00239	.00294
Te	1383.85983	.00023	-.00056	.00019
Dom	356.51952	.00043	-.00208	-.00064
Dl	65.78328	.02138	-.40028	-.32940
Wad	62.11230	.00057	.00935	.01123
Wd	62.29354	.00056	.00913	.01099
Wf	18.06003	.00049	.02940	.03101
Wkd	62.33712	.00057	.00929	.01117
Waq	50.59408	.00025	-.00587	-.00505
Wq	54.94997	.00027	-.00596	-.00507
Wkq	50.60451	.00025	-.00586	-.00505

ORDER STATISTICS

VARIABLE	MAXIMUM	MINIMUM	RANGE	MIDRANGE
Vt	.00588	0.00000	.00588	.00294
Te	.00451	-.00464	.00915	-.00007
Dom	.00723	-.01026	.01749	-.00151
Dl	-.05220	-.87380	.82160	-.46300
Wad	.02175	.00095	.02080	.01135
Wd	.02172	.00105	.02067	.01139
Wf	.04077	.02337	.01740	.03207
Wkd	.02173	.00095	.02078	.01134
Waq	-.00174	-.01145	.00971	-.00660
Wq	-.00152	-.01207	.01055	-.00680
Wkq	-.00174	-.01144	.00970	-.00659

Table E.5b Statistical Analysis of the Difference between
the Saturated (A) and Unsaturated (EA) Flux
Linkage Model, Step Change in E_{FD}

VARIABLE	VARIANCE	STANDARD DEV.	COEF OF SKEWNESS	COEF OF KURTOSIS
Vt	.00000	.00130	-.49612	-1.09126
Te	.00000	.00007	.03066	-1.29666
Dom	.00000	.00045	-.62892	-.68674
Dl	.01776	.13328	.47515	-1.11431
Wad	.00002	.00430	-.48564	-1.10250
Wd	.00002	.00400	-.48114	-1.10740
Wf	.00001	.00312	-.80334	-.72211
Wkd	.00002	.00428	-.49114	-1.09770
Waq	.00000	.00176	.49301	-1.09814
Wq	.00000	.00193	.49279	-1.09787
Wkq	.00000	.00175	.49365	-1.09968

VARIABLE	COEF VARIATION	STANDARD ERROR OF THE MEAN	90 % CONFIDENCE INTERVAL ON MEAN LOWER LIMIT	UPPER LIMIT
Vt	89.31576	.00012	-.00165	-.00126
Te	95.36870	.00001	-.00009	-.00007
Dom	58.21097	.00004	.00071	.00084
Dl	140.93967	.01187	.07489	.11425
Wad	111.24236	.00038	-.00450	-.00323
Wd	116.94410	.00036	-.00401	-.00283
Wf	14.86930	.00028	.02049	.02141
Wkd	111.78926	.00038	-.00446	-.00320
Waq	1008.78950	.00016	-.00009	.00043
Wq	331.86426	.00017	.00030	.00087
Wkq	1026.65779	.00016	-.00009	.00043

ORDER STATISTICS

VARIABLE	MAXIMUM	MINIMUM	RANGE	MIDRANGE
Vt	.00001	-.00409	.00410	-.00204
Te	.00005	-.00019	.00024	-.00007
Dom	.00140	-.00009	.00149	.00065
Dl	.36630	-.05670	.42300	.15480
Wad	.00101	-.01258	.01359	-.00579
Wd	.00112	-.01151	.01263	-.00520
Wf	.02398	.01389	.01009	.01094
Wkd	.00100	-.01251	.01351	-.00576
Waq	.00378	-.00180	.00558	.00099
Wq	.00454	-.00159	.00613	.00148
Wkq	.00377	-.00180	.00557	.00099

T_e

Figure E.4.a.1 Statistical Plots of A-C for a T_m Disturbance,

Data for T_e

Figure E.4.a.2 Statistical Plots of A-C for a T_m Disturbance,

Data for $\Delta\omega$

D1

PERCENT UNDER
NORMAL PROBABILITY PLOT

Figure E.4.a.3 Statistical Plots of A-C for a T_m Disturbance,

Data for δ

Figure E.4.a.4 Statistical Plots of A-C for a T_m Disturbance,

Data for V_t

T_e

NORMAL PROBABILITY PLOT

Figure E.4.b.1 Statistical Plots of A-C for a E_{PD} Disturbance,

Data for T_e

Dom

Figure E.4.b.2 Statistical Plots of A-C for a E_{FD} Disturbance,

Data for $\Delta\omega$

DI

Figure E.4.b.3 Statistical Plots of A-C for a E_{FD} Disturbance,

Data for δ

PERCENT UNDER
NORMAL PROBABILITY PLOT

Figure E.4.b.4 Statistical Plots of A-C for a E_{FD} Disturbance,

Data for V_t

**Table E.6a Statistical Analysis of the Difference between
the Flux Linkage Model when Fully Saturated and
Partially Saturated, Step Change in T_m**

Variable	Variance	Standard Dev.	Skewness	IF OF KURTOSIS
Vt	.00000	.00158	.11632	-1.21715
Te	.00001	.00234	.01425	-.95393
Dom	.00002	.00443	-.07880	-.95831
Dl	.04317	.20777	-.44866	-.78846
Wad	.00003	.00545	.12202	-1.15369
Wd	.00003	.00535	.18839	-1.06092
Wf	.00002	.00466	.30473	-1.20671
Wkd	.00003	.00543	.12517	-1.15503
Waq	.00001	.00241	-.40528	-.74535
Wq	.00001	.00264	-.43062	-.75227
Wkq	.00001	.00241	-.40585	-.74486

VARIABLE	COEF VARIATION	STANDARD ERROR OF THE MEAN	90 % CONFIDENCE INTERVAL ON MEAN	
			LOWER LIMIT	UPPER LIMIT
Vt	68.72449	.00014	.00206	.00253
Te	1962.58187	.00021	-.00046	.00023
Dom	382.24197	.00040	-.00182	-.00051
Dl	77.37356	.01851	-.29920	-.23785
Wad	68.06054	.00049	.00720	.00881
Wd	69.40728	.00048	.00692	.00850
Wf	79.47955	.00042	.00518	.00656
Wkd	68.34697	.00048	.00715	.00875
Waq	73.90662	.00021	-.00362	-.00290
Wq	75.47053	.00024	-.00389	-.00311
Wkq	73.95225	.00021	-.00361	-.00290

ORDER STATISTICS

VARIABLE	MAXIMUM	MINIMUM	RANGE	MIDRANGE
Vt	.00501	0.00000	.00501	.00251
Te	.00416	-.00418	.00834	-.00001
Dom	.00672	-.00924	.01596	-.00126
Dl	0.00000	-.70920	.70920	-.35460
Wad	.01770	0.00000	.01770	.00885
Wd	.01765	-.00001	.01766	.00882
Wf	.01484	0.00000	.01484	.00742
Wkd	.01768	0.00000	.01768	.00884
Waq	0.00000	-.00846	.00846	-.00423
Wq	0.00000	-.00919	.00919	-.00460
Wkq	0.00000	-.00846	.00846	-.00423

Table E.6b Statistical Analysis of the Difference between
Flux Linkage Model when Fully Saturated and
Partially Saturated, Step Change in E_{FD}

VARIABLE	VARIANCE	STANDARD DEV.	COEF OF SKEWNESS	COEF OF KURTOSIS
Vt	.00000	.00153	-.33823	-1.19841
Te	.00000	.00009	-.32284	-.70543
Dom	.00000	.00042	-1.05544	.04058
Dl	.02433	.15597	.31559	-1.21148
Wad	.00003	.00503	-.32908	-1.20589
Wd	.00002	.00467	-.32396	-1.20900
Wf	.00002	.00408	-.53669	-1.05673
Wkd	.00003	.00501	-.33343	-1.20462
Waq	.00000	.00206	.33541	-1.20154
Wq	.00001	.00227	.33460	-1.20117
Wkq	.00000	.00206	.33676	-1.20224

VARIABLE	COEF VARIATION	STANDARD ERROR OF THE MEAN	90 % CONFIDENCE INTERVAL ON MEAN LOWER LIMIT	UPPER LIMIT
Vt	79.78196	.00014	-.00214	-.00169
Te	379.74573	.00001	-.00004	-.00001
Dom	46.38336	.00004	.00085	.00097
Dl	80.25647	.01390	.17131	.21737
Wad	79.72368	.00045	-.00705	-.00557
Wd	79.72405	.00042	-.00654	-.00517
Wf	91.56199	.00036	-.00506	-.00385
Wkd	80.02350	.00045	-.00700	-.00552
Waq	81.59812	.00018	.00222	.00283
Wq	81.35940	.00020	.00245	.00312
Wkq	81.70277	.00018	.00222	.00283

ORDER STATISTICS

VARIABLE	MAXIMUM	MINIMUM	RANGE	MIDRANGE
Vt	0.00000	-.00484	.00484	-.00242
Te	.00013	-.00023	.00036	-.00005
Dom	.00139	0.00000	.00139	.00070
Dl	.49360	0.00000	.49360	.24680
Wad	0.00000	-.01592	.01592	-.00796
Wd	0.00000	-.01477	.01477	-.00739
Wf	0.00000	-.01287	.01287	-.00644
Wkd	0.00000	-.01585	.01585	-.00793
Waq	.00652	0.00000	.00652	.00326
Wq	.00718	0.00000	.00718	.00359
Wkq	.00652	0.00000	.00652	.00326

Figure E.5.a.1 Statistical Plots of A-D for a T_m Disturbance,

Data for T_e

Figure E.5.a.2 Statistical Plots of A-D for a T_m Disturbance,

Data for $\Delta\omega$

Figure E.5.a.3 Statistical Plots of A-D for a T_m Disturbance,

Data for δ

PERCENT UNDER
NORMAL PROBABILITY PLOT

Figure E.5.a.4 Statistical Plots of A-D for a T_m Disturbance,

Data for V_t

T_e

Figure E.5.b.1 Statistical Plots of A-D for a E_{FD} Disturbance,

Data for T_e

Dom

Figure E.5.b.2 Statistical Plots of A-D for a E_{FD} Disturbance,

Data for $\Delta\omega$

D1

Figure E.5.b.3 Statistical Plots of A-D for a E_{FD} Disturbance,

Data for δ

PERCENT UNDER
NORMAL PROBABILITY PLOT

Figure E.5.b.4 Statistical Plots of A-D for a E_{FD} Disturbance,

Data for V_t

Table E.7a Statistical Analysis of the Difference between
the Flux Linkage (Saturated) Model and the E'' Model
with Partial Saturation, Step Change in T_m

VARIABLE	VARIANCE	STANDARD DEV.	COEF OF SKEWNESS	COEF OF KURTOSIS
Vt	.000000	.00043	-.09962	-.99132
Te	.000002	.00410	.20138	-.29336
Dom	.000006	.00797	.05457	-.12150
Dl	.02709	.16458	.34059	-.18689
Wad	.000000	.00161	-.51694	-.45885
Wd	.000001	.00276	-.38496	-.35744
Wf	.000000	.00192	-.48187	-.52434
Wkd	.000000	.00118	-.72276	-.42506
Waq	.000000	.00132	.47402	.10007
Wq	.000000	.00146	.48291	.12246
Wkq	.000000	.00131	.47491	.10920

VARIABLE	COEF VARIATION	STANDARD ERROR OF THE MEAN	90 % CONFIDENCE INTERVAL ON MEAN LOWER LIMIT	UPPER LIMIT
Vt	82.07386	.00004	.00046	.00059
Te	1305.11698	.00037	-.00029	.00092
Dom	4804.81617	.00071	-.00134	.00101
Dl	397.40681	.01466	-.06571	-.01711
Wad	117.71620	.00014	.00113	.00161
Wd	229.38449	.00025	.00080	.00161
Wf	137.41648	.00017	.00111	.00168
Wkd	76.87399	.00011	.00136	.00171
Waq	268.95512	.00012	-.00068	-.00029
Wq	267.35295	.00013	-.00076	-.00033
Wkq	268.69094	.00012	-.00068	-.00029

ORDER STATISTICS

VARIABLE	MAXIMUM	MINIMUM	RANGE	MIDRANGE
Vt	.00126	-.00038	.00164	.00044
Te	.00994	-.00827	.01821	.00084
Dom	.02075	-.01792	.03067	.00142
Dl	.36410	-.36590	.73000	-.00090
Wad	.00388	-.00257	.00645	.00066
Wd	.00624	-.00553	.01177	.00036
Wf	.00427	-.00325	.00752	.00051
Wkd	.00317	-.00135	.00452	.00091
Waq	.00295	-.00300	.00595	-.00003
Wq	.00330	-.00333	.00663	-.00002
Wkq	.00295	-.00300	.00595	-.00003

Table E.7b Statistical Analysis of the Difference between
Flux Linkage (Saturated) Model and the E'' Model
with Partial Saturation, Step Change in E_{FD}

VARIABLE	VARIANCE	STANDARD DEV.	COEF OF SKEWNESS	COEF OF KURTOSIS
Vt	.00000	.00024	.77341	-.86892
Te	.00000	.00013	-.23576	-.09527
Dom	.00000	.00030	1.05132	.46817
Dl	.00067	.02593	-.77307	-.89965
Wad	.00000	.00083	.64719	-1.08157
Wd	.00000	.00078	.65649	-1.05050
Wf	.00000	.00108	.59277	-1.05885
Wkd	.00000	.00080	.70564	-1.03598
Waq	.00000	.00034	-.74355	-.96223
Wq	.00000	.00037	-.75505	-.94563
Wkq	.00000	.00034	-.73926	-.97394

VARIABLE	COEF VARIATION	STANDARD ERROR OF THE MEAN	90 % CONFIDENCE INTERVAL ON MEAN LOWER LIMIT	UPPER LIMIT
Vt	57.84022	.00002	-.00045	-.00038
Te	10960.27954	.00001	-.00002	.00002
Dom	257.17700	.00003	.00007	.00016
Dl	66.97163	.00231	.03489	.04255
Wad	72.37869	.00007	-.00127	-.00102
Wd	75.55690	.00007	-.00115	-.00092
Wf	90.27541	.00010	-.00136	-.00104
Wkd	61.99793	.00007	-.00142	-.00118
Waq	65.18355	.00003	.00047	.00057
Wq	64.81248	.00003	.00052	.00063
Wkq	65.04123	.00003	.00047	.00056

ORDER STATISTICS

VARIABLE	MAXIMUM	MINIMUM	RANGE	MIDRANGE
Vt	.00009	-.00065	.00074	-.00028
Te	.00029	-.00032	.00061	-.00002
Dom	.00094	-.00031	.00125	.00031
Dl	.06550	-.01170	.07720	.02690
Wad	.00049	-.00198	.00247	-.00075
Wd	.00047	-.00183	.00230	-.00068
Wf	.00101	-.00236	.00337	-.00068
Wkd	.00025	-.00207	.00232	-.00091
Waq	.00086	-.00012	.00098	.00037
Wq	.00095	-.00013	.00108	.00041
Wkq	.00086	-.00011	.00097	.00038