

Table of Contents

Table of Contents	I
List of Variables and Parameters	IX
List of Figures	XIII
List of Tables	XIX
1. Introduction	1
1.1 THE MOTIVATION.....	1
1.2 THE OBJECTIVES	2
1.2.1 To Deepen the Knowledge of Hydroelectric System Models	2
1.2.2 To Design Controllers from Well Proven Models	2
1.3 RESEARCH AIMS.....	2
1.3.1 Hydroelectric Generation Systems	2
1.3.2 The Frequency Control.....	5
1.4 ORGANISATION OF THE DISSERTATION	8
2. Previous Related Work	11
2.1 MODELS OF HYDROELECTRIC SYSTEMS	11
2.1.1 Nonlinear Models	12
2.1.2 Linearized Models.....	13
2.1.3 Models for Particular Applications.	14
2.2 FREQUENCY (SPEED) CONTROLLERS.....	15
2.2.1 Controllers Designed from Linearized Models	15

2.2.1.1	Classical Controllers.....	15
2.2.1.2	Controllers with Specific Characteristics	17
2.2.2	Controllers Designed from Nonlinear Models.....	18
2.2.3	Controller Implementation.....	18
2.3	CONCLUSIONS	18
3.	Hydroelectric System Models	21
3.1	PRELIMINARY CONCEPTS	21
3.1.1	Definitions.....	23
3.1.2	System Dynamic Equations	24
3.1.3	Linearized Equations.....	25
3.1.4	Classification of the Models	26
3.2	NONLINEAR MODELS	26
3.2.1	Models with Surge Tank Effects.....	28
3.2.1.1	Model with an elastic water column in the penstock and a non-elastic water column in the tunnel (Kundur, 1994) - Model K5, K51, K52	28
3.2.1.2	Model with an elastic water column in the penstock and a non-elastic water column in the tunnel (IEEE Working Group, 1992; Quiroga and Riera, 1999) - Models WG5, QR52, QR51.....	29
3.2.1.3	Model with non-elastic water columns (Kundur, 1994) – Model K4	31
3.2.1.4	Model with non-elastic water columns (IEEE Working Group, 1992) – Model WG4.....	31
3.2.1.5	Comparisons between the models with an elastic water column in the penstock and a non-elastic water column in the tunnel (3.2.1.1 and 3.2.1.2)	31
3.2.1.6	Comparison between models with non-elastic water columns (3.2.1.3 and 3.2.1.4)	33
3.2.2	Models with no Surge Tank Effects.....	34
3.2.2.1	Model with an elastic water column in the penstock (Kundur, 1994) – Models K3, K32, K31	34
3.2.2.2	Model with an elastic water column in the penstock (IEEE Working Group, 1992; Quiroga and Riera, 1999) – Models WG3, QR33, QR32, QR31	34
3.2.2.3	Model with a non-elastic water column in the penstock (Kundur, 1994) – Model K2	35
3.2.2.4	Model with a non-elastic water column in the penstock (IEEE Working Group, 1992) – Model WG2	35
3.2.2.5	Comparison between the models 3.2.2.1 and 3.2.2.2	35

3.3	LINEARIZED MODELS	36
3.3.1	Models with Surge Tank Effects	37
3.3.1.1	Model with an elastic water column in the penstock and a non-elastic water column in the tunnel (Quiroga, 1998a) – Model Q_{lin}	37
3.3.1.2	Model with non-elastic water columns (Quiroga, 1998a) – Model Q_{lin0}	37
3.3.2	Models with no Surge Tank Effects	37
3.3.2.1	Model with an elastic water column in the penstock (Kundur, 1994) – Model K_{lin}	37
3.3.2.2	Models with a non-elastic water column in the penstock (Gaden, 1945) – Model G_{lin0}	38
3.4	CONCLUSIONS OF THE PRESENTED MODELS	38
3.5	STATIC ANALYSIS	39
3.5.1	Determination of the Flow of the Turbine in Steady State	40
3.5.1.1	Deduction of \bar{U}_{tss} for a nonlinear model with surge tank effects	40
3.5.1.2	Deduction of \bar{U}_{tss} for a nonlinear model with no surge tank effects	41
3.5.1.3	Determination of \bar{U}_0 used in the models of Kundur (1994)	41
3.5.1.4	Determination of \bar{U}_0 by using the comparison between equations	43
3.5.1.5	Verification of supposition made in 3.5.1.4	43
3.5.2	Determination of the Mechanical Power	44
3.5.2.1	Calculations for nonlinear models with and with no surge tank effects	44
3.5.2.2	Calculations for a linearized model with and with no surge tank effects	45
3.5.2.3	Calculation of the gate opening (\bar{G}) for $\bar{P}_{mecess} = 0$	46
3.6	TIME DOMAIN ANALYSIS OF MODELS	48
3.6.1	Nonlinear Models with Surge Tank Effects	48
3.6.1.1	Models WG4, QR51, QR52, WG5	48
3.6.1.2	Models K4, K51, K52	52
3.6.2	Linearized Models with Surge Tank Effects	54
3.6.2.1	Model Q_{lin0}	55
3.6.3	Nonlinear Models with no Surge Tank Effects	56
3.6.3.1	Models WG2, QR31, QR32, QR33	57
3.6.3.2	Models K2, K31, K32	58
3.6.4	Linearized Model with no Surge Tank Effects	59
3.6.4.1	Model K_{lin}	59

3.6.4.2	Classic linear model with ideal turbine (Gaden, 1945) - Model G_{lin0}	60
3.6.5	Conclusions of Time Domain Analysis	60
3.7	FREQUENCY RESPONSE ANALYSIS OF MODELS.....	62
3.7.1	Models with no Surge Tank Effects.....	62
3.7.1.1	Models K_{lin} and G_{lin0}	62
3.7.1.2	Stability study.....	63
3.7.2	Models with Surge Tank Effects.....	64
3.7.2.1	Models Q_{lin} and Q_{lin0}	64
3.7.2.2	Stability Study	66
3.8	SUGGESTIONS FOR MODELLING HYDROELECTRIC POWER PLANTS.....	69
3.8.1	Models with Surge Tank Effects.....	69
3.8.1.1	Nonlinear Models.....	69
3.8.1.2	Linearized Models.....	70
3.8.2	Models with no Surge Tank Effects.....	70
3.8.2.1	Nonlinear Models.....	70
3.8.2.2	Linearized Models.....	70
3.9	SUMMARY	70
4.	Identification of a Hydroelectric Power Plant	73
4.1	CHARACTERISTICS OF THE HYDROELECTRIC POWER STATION	74
4.2	GENERAL NONLINEAR EQUATIONS	75
4.2.1	Adjustment of the Equations.....	79
4.2.2	Output Power Adjustment.....	79
4.2.3	Surge Tank Natural Period.....	80
4.3	SIMULATION RESULTS.....	81
4.3.1	Identification Using the Models A.....	81
4.3.2	Identification Using the Models B.....	84
4.3.3	Identification Using the Model C.....	86
4.3.4	Identification Using the Model D	87
4.4	COMPARATIVE STUDY OF THE QUADRATIC ERROR	88
4.5	SUMMARY AND CONCLUSIONS.....	89

5. Nonlinear Controllers (I): Based on the Partial State Feedback Linearization Technique 91

5.1	INTRODUCTION	92
5.2	MODELS FOR HYDRAULIC TURBINES.....	94
5.3	NONLINEAR CONTROLLERS FOR HYDRAULIC TURBINES WITH NO SURGE TANK EFFECTS 95	
5.3.1	The Cost Functions.....	95
5.3.1.1	The Cost Function A	96
5.3.1.2	The Cost Function B	96
5.3.2	PID Controllers.....	96
5.3.2.1	Fixed PID controllers	96
5.3.2.2	PI-PD controller	97
5.3.2.3	Gain Scheduling Controllers	97
5.3.3	Nonlinear Controllers	98
5.3.4	The Zero Dynamics of Nonlinear System with no Surge Tank Effects	101
5.3.5	Comparative Studies Using $f_{\text{cost(A)}}$	102
5.3.5.1	Comparison of Rotor Speed Behaviour for Different Load Changes	104
5.3.5.2	Comparison of Cost Function Values ($f_{\text{cost(A)}}$)	105
5.3.6	Controller Adjustment Surfaces Using $f_{\text{cost(A)}}$	106
5.3.6.1	Adjustment for the PI-PD Controller	107
5.3.6.2	Adjustment for the Nonlinear Controller NL B	108
5.3.7	Comparative Studies Using $f_{\text{cost(B)}}$	109
5.3.7.1	Comparison of Cost Function Values ($f_{\text{cost(B)}}$).....	110
5.3.8	Controllers Adjustment Surfaces Using $f_{\text{cost(B)}}$	111
5.3.8.1	Adjustment for the PID Controller.....	111
5.3.8.2	Adjustment for the Nonlinear Controller NL B	113
5.4	NONLINEAR CONTROLLERS FOR HYDRAULIC TURBINES WITH SURGE TANK EFFECTS.....	114
5.4.1	Nonlinear Controllers.....	114
5.4.2	The Zero Dynamics of Nonlinear System with Surge Tank Effects	117
5.4.3	Comparative Studies Using $f_{\text{cost(A)}}$	119
5.4.3.1	Comparison of Rotor Speed Behaviour for Different Load Changes	119
5.4.3.2	Comparison of Cost Function Values $f_{\text{cost(A)}}$	120

5.4.4	Controller Adjustment Surfaces Using $f_{\text{cost(A)}}$	121
5.4.4.1	Adjustment for the PI-PD Controller	121
5.4.4.2	Adjustment for the Nonlinear Controller NL D	122
5.4.5	Comparative Studies Using $f_{\text{cost(B)}}$	123
5.4.5.1	Comparison of Cost Function Values $f_{\text{cost(B)}}$	123
5.4.6	Controller Adjustment Surfaces Using $f_{\text{cost(B)}}$	124
5.4.6.1	Adjustment for the PI-PD Controller	124
5.4.6.2	Adjustment for the Nonlinear Controller NL D	126
5.5	LOAD REJECTION STUDIES	127
5.5.1	Study for the Controller NL B	127
5.5.2	Study for the Controller NL D	128
5.6	SUMMARY AND CONCLUSIONS	128
6.	Nonlinear Controllers (II): Based on the Lyapunov Function Technique	131
6.1	INTRODUCTION	132
6.2	NONLINEAR CONTROLLERS FOR HYDRAULIC PLANTS WITH SURGE TANK EFFECTS ...	133
6.2.1	Models for Hydraulic Turbines with Surge Tank Effects	133
6.2.2	Construction of a Lyapunov Function	134
6.2.3	Consideration of ‘ a_2 ’: Alternative Cases	139
6.3	COMPARATIVE STUDIES	140
6.3.1	Comparisons of Hydro Plants with Surge Tank Effects	140
6.3.1.1	Comparison of Cost Function Values Using $f_{\text{cost(A)}}$	140
6.3.1.2	Comparison of Rotor Speed Behaviour	142
6.3.1.3	Comparison of Cost Function Values Using $f_{\text{cost(B)}}$	142
6.3.2	Comparison of Hydro Plants with no Surge Tank Effects	143
6.3.2.1	Comparison of Cost Function Values Using $f_{\text{cost(A)}}$	142
6.3.2.2	Comparison of Cost Function Values Using $f_{\text{cost(B)}}$	145
6.4	LOAD REJECTION STUDIES	146
6.4.1	Study for the Lyapunov 2 Controller	146
6.4.2	Study for the Lyapunov 4 and Lyapunov 51 Controllers	146
6.4	SUMMARY AND CONCLUSIONS	148
7.	Conclusions and Contributions	149
7.1	CONCLUSIONS	149

7.2 GENERAL CONTRIBUTIONS.....	152
7.3 FUTURE WORK.....	153
Appendix A	157
Appendix B	165
References	169

List of Variables and Parameters

a : wave velocity [m/s].

A : cross section [m²].

A_c : tunnel cross section [m²].

A_p : penstock cross section [m²].

A_s : surge tank cross section [m²].

A_t : turbine gain [pu].

$c_{1,2,3}$: weight coefficients of the cost function [pu].

D : load-damping constant [pu].

D_1 : turbine damping [pu/pu].

$D \cdot \bar{\omega}_l$: frequency-sensitive load [pu].

E : Young's modulus of pipe wall material.

f : wall thickness of penstock [m].

f_0 : surge chamber orifice head loss coefficient [pu].

f_p, f_{p1} : penstock head loss coefficient [pu].

f_{p2} : tunnel head loss coefficient [pu].

g : acceleration due to gravity [m²/s].

G : gate opening [%]

\bar{G} : gate opening [pu].

\bar{G}_0 : initial value of the gate opening [pu].

\bar{G}_d : desired value of the gate opening [pu].
 H : inertia constant [MW·s/MVA].
 \bar{H} : hydraulic head at gate [pu].
 H_0 : total head [m].
 \bar{H}_0 : initial steady state value of \bar{H} [pu].
 H_{base} : base head [m].
 $H_1 + H_{12}$: head losses [m].
 \bar{H}_1 : head loss in the penstock [pu].
 \bar{H}_{12} : head loss in the tunnel [pu].
 \bar{H}_r : surge tank head [pu].
 \bar{H}_{rSS} : steady state value of the surge tank head [pu].
 \bar{H}_t : turbine head [pu].
 k_f : Head loss constant due to friction [pu].
 K_p : proportional gain of a PID.
 K_{p1} : proportional gain of a PID.
 K_i : integral gain of a PID.
 K_d : derivative gain of a PID.
 L_c : length of the tunnel [m].
 L_p : length of the penstock [m].
 P_{elec} : electric power [MW].
 $\bar{P}_{\text{electric}}$: electric power [pu], where: $\bar{P}_{\text{electric}} = \bar{P}_{\text{load}} + D \cdot \bar{\omega}_r$.
 $\bar{P}_{\text{mechanical}}$: turbine mechanical power [pu].
 \bar{P}_{mechSS} : steady state value of the turbine mechanical power [pu].
 $\bar{P}_{\text{load}} \equiv P_1$: non-frequency-sensitive load [pu].
 Q : flow [m³/s].
 Q_{base} : base flow [m³/s].
 Q_{max} : maximum low [m³/s].
 Q_{rated} : rated flow [m³/s].
 $R_{1,2,3,4}$: feedback gains [pu].

R_p : temporary droop [pu].
 T : surge tank natural period [s].
 T_e : elastic time [s].
 T_{ec} : elastic time of the tunnel [s].
 T_{ep} : elastic time of the penstock [s].
 T_g : main servo time constant [s].
 T_p : pilot valve and servomotor time constant [s].
 $T_{\bar{w}}$: water starting time at any load [s].
 T_W : water starting time at rated or base load [s].
 T_{WC} : water starting time of the tunnel at rated or base load [s].
 T_{WP} : water starting time of the penstock at rated or base load [s].
 u : control effort [pu].
 U : water velocity [m/s]
 \bar{U} : water velocity [pu].
 \bar{U}_0 : initial steady state value of water velocity or steady-state flow [pu].
 \bar{U}_c : water velocity in the tunnel or tunnel flow [pu].
 \bar{U}_{css} : steady state value of the tunnel flow [pu].
 \bar{U}_p : water velocity in the penstock or penstock flow [pu].
 U_{rated} : rated water velocity [m/s].
 \bar{U}_t : water velocity in the turbine or turbine flow [pu].
 \bar{U}_{tss} : steady state value of the turbine flow [pu].
 \bar{U}_s : water velocity in the surge tank or surge tank flow [pu].
 \bar{U}_{NL} : no-load flow [pu].
 x_1, x_2, x_3, x_4 : state variables [pu].
 x, y, z, w : state variables [pu].
 z_1, z_2, z_3, z_4 : state variables [pu].
 z_0 : hydraulic surge impedance of the conduit.
 z_c : hydraulic surge impedance of the tunnel.
 z_n : normalised hydraulic surge impedance of the conduit.
 z_p : hydraulic surge impedance of the penstock.

$\Delta\bar{P}_m$: deviation of the mechanical power [pu].

$\Delta\bar{\omega}$: deviation of the rotor speed [pu].

ϕ : internal penstock diameter [m].

ϕ_i : initial diameter of the penstock [m].

ϕ_f : final diameter of the penstock [m].

Φ_c : friction coefficient of the tunnel [pu].

Φ_p : friction coefficient of the penstock [pu].

κ : bulk modulus of water [kg/m.s²].

$\eta(\bar{G})$: nonlinear function [pu].

ρ : density of water [kg/m³].

ω : angular frequency [rad/s] ($s=j\omega$).

$\bar{\omega}_r$: rotor speed [pu].

$\bar{\omega}_{ref}$: reference speed [pu].

List of Figures

Figure 1.1: Representation of a hydroelectric power plant	4
Figure 1.2: Functional block diagram that shows the relation between the hydroelectric system and the controls for a complete system.....	6
Figure 3. 1: Plot of the distribution of parameters in a hydraulic power plant.....	23
Figure 3. 2: Plot of the distribution of heads and flows in a hydraulic power plant	23
Figure 3. 1: Block Diagram of the hydroelectric system used in the models of Kundur (1994)	26
Figure 3.4: Functional diagram of model WG5 from the IEEE Working Group (1992) including associated dynamics.....	30
Figure 3. 5: Diagram of heads and flows distribution in models WG3, QR33, QR32, QR31 and WG2	36
Figure 3.6: Plot of \bar{U}_0 in function of the variable \bar{G} for two hydroelectric power stations ...	42
Figure 3.7: Mechanical power generated by the turbine in hydroelectric plants with surge tank effects as function of \bar{G}	46
Figure 3.8: Representation of the block used for the calculation of the hyperbolic tangent (model WG5).....	48
Figure 3.9: Representation of the block that can be used for the calculation of the hyperbolic tangent function in the models WG4 (n=0), QR51 (n=1) and QR52 (n=2).....	49
Figure 3.10: Comparison among the models WG4, QR51, QR52 and WG5, detail	51

Figure 3.11: Comparison among the models WG4, QR51, QR52 and WG5	51
Figure 3.12: Block diagram for the models of Kundur (1994) and his derived models	52
Figure 3.13: Comparison among the models K4, K51 and K52, detail	53
Figure 3.14: Comparison among the models K4, K51 and K52	53
Figure 3.15: Simulation of the linearized model Q_{lin0} , for a variation of 0.01 [pu] in the gate opening, detail	55
Figure 3.16: Simulation of the linearized model Q_{lin0} , for a variation of 0.01 [pu] in the gate opening	55
Figure 3.17: Functional scheme of a model WG3 from (IEEE Working Group, 1992)	56
Figure 3.18: Comparison among the models WG2, QR31, QR32, QR33 and WG3	57
Figure 3.19: Comparison among the models K2, K31 and K32	58
Figure 3.20: Simulation of the model K_{lin} ($n=0$) by using the parameters of G-Gilboa 3, St. Lawrence 32 and Niagara 1	59
Figure 3.21: Simulation of the classic linear model G_{lin0}	60
Figure 3.22: Bode plot for models of K_{lin} , approximations $n = 0, 1$. Parameters B Gilboa3 ..	62
Figure 3.23: Nyquist diagram for the model of K_{lin} , approximation $n = 0$. Parameters from B Gilboa3 ..	63
Figure 3.24: Nyquist diagram for the model of K_{lin} , approximation $n = 1$. Parameters from B Gilboa3 ..	63
Figure 3.25: Bode plot for the model of Q_{lin0} , approximation $n = 0$. Parameters from (IEEE Working Group, 1992)	64
Figure 3.26: Bode plot for the model of Q_{lin} , approximations $n = 1, 2$. Parameters from (IEEE Working Group, 1992)	65
Figure 3.27: Bode plot for the model of Q_{lin0} and Q_{lin} , approximations $n = 0, 1$. Parameters from Appalachia power plant	65
Figure 3.28: Nyquist diagram for the model Q_{lin} , approximation $n = 0$. Parameters from (IEEE Working Group, 1992)	66
Figure 3.29: Nyquist diagram for the model of Q_{lin} , approximation $n = 1$. Parameters from (IEEE Working Group, 1992)	67
Figure 3.30: Detail of Figure 3.29	67

Figure 3.31: Nyquist diagram for the model Q_{lin} , approximation $n = 2$. Parameters from (IEEE Working Group, 1992).....	68
Figure 3.32: Detail of Figure 3.31	68
Figure 4.1: Plot of heads and flows distribution in a hydroelectric plant with surge tank effects	74
Figure 4.2: Functional diagram for a general nonlinear model with surge tank effects	77
Figure 4.3: Schematic representation of the “In-Out” block used to calculate the exact hyperbolic tangent given by the mathematical expression $z_p \cdot \tanh(T_{ep} \cdot s)$	78
Figure 4.4: Representation of the block used to calculate the approximations $n=0$, $n=1$ and $n=2$ of the hyperbolic tangent function	78
Figure 4.5: Plot of the nonlinear function $\eta(\bar{G})$ calculated by the quadratic and cubic polynomials.....	80
Figure 4.6: Identification of Susqueda using the Models A	82
Figure 4.7: Identification of Susqueda using the Models A	83
Figure 4.8: Detail of Figure 4.7	83
Figure 4.9: Identification of Susqueda using the Models A	83
Figure 4.10: Detail of Figure 4.9	83
Figure 4.11: Identification of Susqueda using the Models A	83
Figure 4.12: Detail of Figure 4.11	83
Figure 4.13: Identification of Susqueda using the Models A	83
Figure 4.14: Detail of Figure 4.13	83
Figure 4.15: Identification of Susqueda using the Models B	85
Figure 4.16: Identification of Susqueda using the Model C	86
Figure 4.17: Identification of Susqueda using the Model C	86
Figure 4.18: Identification of Susqueda using the Model D	87
Figure 4.19: Identification of Susqueda using the Model A	88
Figure 4.20: Detail of Figure 4.19	88

Figure 5.1: Functional block diagram showing the relation between the hydroelectric system and the controls for a complete system.....	93
Figure 5.2: General speed control scheme for a generic controller.....	94
Figure 5.3: PID Controller	97
Figure 5.4: PI-PD Controller.....	97
Figure 5.5: Nonlinear Controller A (NL A).....	100
Figure 5.6: Nonlinear Controller B (NL B).....	100
Figure 5.7: General speed control scheme for the controllers NL A or NL B	101
Figure 5.8: Comparison of rotor speed	104
Figure 5.9: Comparison of rotor speed	104
Figure 5.10: Comparison of rotor speed	105
Figure 5.11: Comparison of rotor speed	105
Figure 5.12: Comparison of rotor speed	105
Figure 5.13: Comparison of rotor speed	105
Figure 5.14: Comparison of cost function values ($f_{\text{cost(A)}}$)	106
Figure 5.15: Adjustment surface for the PI-PD controller ($f_{\text{cost(A)}}$)	107
Figure 5.16: Plane $K_i = 0.7$	107
Figure 5.17: Plane $K_p = 0.5$	107
Figure 5.18: Adjustment surface for the controller NL B ($f_{\text{cost(A)}}$)	108
Figure 5.19: Plane $K_i = 0.3$	108
Figure 5.20: Plane $K_p = 1.5$	108
Figure 5.21: Comparison of cost function ($f_{\text{cost(B)}}$).....	111
Figure 5.22: Adjustment surface for the PID controller ($f_{\text{cost(B)}}$).....	112
Figure 5.23: Plane $K_d = 1.75$	112
Figure 5.24: Plane $K_p = 2.75$	112
Figure 5.25: Adjustment surface for the controller NL B ($f_{\text{cost(B)}}$)	113

Figure 5.26: Plane $K_i = 0.3$	113
Figure 5.27: Plane $K_p = 1.5$	113
Figure 5.28: Nonlinear Controller C (NL C).....	116
Figure 5.29: Nonlinear Controller D (NL D).....	117
Figure 5.30: General speed control scheme for the controllers NL C or NL D.....	117
Figure 5.31: Comparison of rotor speed.....	120
Figure 5.32: Comparison of cost function for the controllers PID, PI-PD, Gain Scheduling PI-PD and NL D ($f_{\text{cost(A)}}$).....	120
Figure 5.33: Adjustment surface for the PI-PD controller ($f_{\text{cost(A)}}$).....	121
Figure 5.34: Plane $K_i = 0.04$	121
Figure 5.35: Plane $K_p = 1$	121
Figure 5.36: Adjustment surface for the controller NL D ($f_{\text{cost(A)}}$).....	122
Figure 5.37: Plane $K_i = 0.75$	122
Figure 5.38: Plane $K_p = 1$	122
Figure 5.39: Comparison of cost function for the controllers: PID, PI-PD and NL D ($f_{\text{cost(B)}}$).....	124
Figure 5.40: Adjustment surface for the PI-PD controller ($f_{\text{cost(B)}}$).....	125
Figure 5.41: Plane $K_i = 0.04$	125
Figure 5.42: Plane $K_p = 1$	125
Figure 5.43: Adjustment surface for the controller NL D ($f_{\text{cost(B)}}$).....	126
Figure 5.44: Plane $K_i = 0.75$	126
Figure 5.45: Plane $K_p = 0.25$	126
Figure 5.46: Load rejection study of the controller NL B for three different loads.....	127
Figure 5.47: Representation of the relation between $f_{\text{cost(A)}}$ and $\Delta\bar{P}_{\text{load}}$	127
Figure 5.48: Load rejection study of the controller NL D for two different loads.....	128
Figure 5.49: Graphic of the relation between $f_{\text{cost(A)}}$ and $\Delta\bar{P}_{\text{load}}$	128
Figure 6.1: General block diagram showing the speed control loop.....	134

Figure 6.2: Comparison of the cost function ($f_{\text{cost(A)}}$) for the Lyapunov 4 and Lyapunov51 controllers	141
Figure 6.3: Comparison of rotor speed	142
Figure 6.4: Comparison of rotor speed, detail.....	142
Figure 6.5: Comparison of the cost function for the controllers: Lyapunov 4, Lyapunov51, NL C, PID, PI-PD and NL D ($f_{\text{cost(B)}}$)	143
Figure 6.6: Comparison of the cost function for the controllers: Lyapunov 2, Gain Scheduling PID, PI-PD and NL B ($f_{\text{cost(A)}}$)	144
Figure 6.7: Comparison of the cost function for the controllers: Lyapunov 2, PI-PD, PID, Gain Scheduling PID and NL B ($f_{\text{cost(B)}}$).....	145
Figure 6.8: Representation of the relation between $f_{\text{cost(B)}}$ and $\Delta\bar{P}_{\text{load}}$	146
Figure 6.9: Load rejection study of the controller Lyapunov 4 for two different loads	147
Figure 6.10: Graphic of the relation between $f_{\text{cost(B)}}$ and $\Delta\bar{P}_{\text{load}}$, Lyapunov 4	147
Figure 6.11: Graphic of the relation between $f_{\text{cost(B)}}$ and $\Delta\bar{P}_{\text{load}}$, Lyapunov51	147

List of Tables

Table 3.1: List of parameters.....	22
Table 3.2: List of variables.....	23
Table 3. 3: Table of nonlinear models.....	27
Table 3. 4: Table of linearized models.....	36
Table 3.5: Parameters for different power plants	47
Table 4.1: Plant Characteristics.....	75
Table 4.2: Conduits Characteristics	75
Table 4.3: Parameters of Susqueda power station.....	76
Table 4.4: Values of the nonlinear function $\eta(\bar{G})$ for different gate positions deduced from experimental tests	79
Table 4.5: Polynomials obtained from the first and third columns of Table 4.4 using the method of the least squares.....	80
Table 4.6: Description of the Models A and their references.....	81
Table 4.7: Description of the Models B and their references.....	84
Table 4.8: Description of the Model C and its references.....	86
Table 4.9: Description of the Model D and its references.....	87

Table 4.10: Quadratic error found using the models A, where the nonlinear function $\eta(\bar{G})$ is approximated by two polynomials with degree 2 and 10	89
Table 5. 1: Parameters of PID, PI-PD, NL A and NL B controllers	103
Table 5. 2: Meanings of the parameters of the controllers.....	103
Table 5. 3: Values of the parameters for the Gain Scheduling PID and the Gain Scheduling PI-PD ($f_{\text{cost(A)}}$)	104
Table 5.4: Parameters of PID, PI-PD, NL A and NL B controllers	109
Table 5.5: Parameter values of the Gain Scheduling PID and Gain Scheduling PI-PD ($f_{\text{cost(B)}}$)	110
Table 5.6: Parameters of the PI-PD, PID, NL C and NL D controllers	119
Table 5.7: Parameters of the PI-PD, PID, NL C and NL D controllers	123