

**MODELING AND SYNTHESIS OF OSCILLATION
DAMPING CONTROLLER UNDER
SYSTEM UNCERTAINTIES**

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**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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DAMPING CONTROLLER UNDER
SYSTEM UNCERTAINTIES**

by

ABHISHEK NAYAK

DEPARTMENT OF ELECTRICAL ENGINEERING

submitted

**in fulfilment of the requirements of the degree of Doctor of Philosophy
to the**



INDIAN INSTITUTE OF TECHNOLOGY DELHI

MARCH 2024

*Dedicated to my family and all those who lost their
life during COVID.*

Certificate

This is to certify that the thesis entitled “**Modeling and Synthesis of Oscillation Damping Controller Under System Uncertainties**”, being submitted by **Abhishek Nayak** to the Department of Electrical Engineering, Indian Institute of Technology Delhi for the award of the degree of Doctor of Philosophy is the record of the bonafide research work carried out by him under my supervision. In my opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree. The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

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Date:

Abhishek Nayak

Abstract

This thesis focuses on damping low-frequency power oscillations in renewable integrated uncertain power systems. The low-frequency power oscillations are associated with large interconnected power systems and can limit the power transfer capacity in the tie-lines and can also lead to rotor-angle instability. However, designing an inter-area oscillation damping controller is a complicated problem as it involves challenges such as modeling of large order renewable integrated power systems, variable operating conditions, network latencies in remote feedback signals, and actuation of control signals. In this aspect, the research work is divided into subtopics, with each focusing on these building blocks in a closed-loop control system.

The large order model of a renewable integrated power grid is addressed by proposing a new model order reduction methodology. In addition, measures are provided for ascertaining the validity of the obtained reduced-order model under uncertainties. These results are obtained using the singular perturbation theory.

The variable operating conditions and complicated modeling are addressed by proposing adaptive damping controllers with input-output structure. Multiple adaptive controller designs are proposed, namely Model Reference Adaptive Control- Proportional Integral, Self-Tuning Control, Model-Free Adaptive Control, and Robust Model Reference Adaptive Controller.

The network latencies in the feedback signal are analyzed, and their impact on the performance of the adaptive controller is discussed. A new delay compensator is proposed, which has the advantage of compensating wide ranges of random delays. In addition, a new package drop compensator is proposed based on dynamic linearization.

The actuation of the damping control signals is analyzed by modulating the powers from the PV based power plant and by excitation system in the synchronous generator. It is observed that the PV based power plant can effectively produce damping control action, and a robust-adaptive control is used for achieving bounded actuation effort.

Rigorous case studies were carried out with the proposed methodologies and observed that significant advantages are achieved, especially under uncertainties.

सारांश

यह थीसिस रिन्यूएबल एनर्जी एकीकृत अनिश्चितताओं के पावर सिस्टम में लौ फ्रीक्वेंसी पावर ओस्किल्लाशंस को सीमित करने पर केंद्रित है। लौ फ्रीक्वेंसी पावर ओस्किल्लाशंस परस्पर से जुड़ी बिजली प्रणालियों में मौजूद होती हैं और टाई-लाइनों में बिजली हस्तांतरण क्षमता को सीमित कर सकते हैं और रोटर-एंगल अस्थिरता भी पैदा कर सकते हैं। हालाँकि एक अंतर-क्षेत्र ओस्किल्लाशंस डंपिंग नियंत्रक को डिजाइन करना एक जटिल समस्या है क्योंकि इसमें बड़े क्रम के रिन्यूएबल एकीकृत बिजली प्रणालि मौजूद होते हैं। इनके कारन मॉडलिंग और परिवर्तनीय परिचालन स्थितियों पैदा होते हैं। साथ में दूरस्थ फीडबैक संकेतों में नेटवर्क विलंबता और नियंत्रण संकेतों के क्रियान्वयन जैसी चुनौतियाँ आती है। इस पहलू में, थीसिस कार्य को उप-विषयों में विभाजित किया गया है, जिनमें नियंत्रण प्रणाली के प्रत्येक विषयों पर ध्यान केंद्रित किया गया है।

रिन्यूएबल एकीकृत पावर ग्रिड का बड़ा मॉडल ऑर्डर होता है। बड़ा मॉडल ऑर्डर को छोटा करने के लिए एक नए मॉडल ऑर्डर रिडक्शन तकनीक का प्रस्ताव किया गया है। इसके अलावा, अनिश्चितताओं में छोटा-ऑर्डर मॉडल की मान्यता सुनिश्चित करने के लिए उपाय प्रदान किया गया है। ये परिणाम सिंगुलर परतुरबतिओं सिद्धांत का उपयोग करके प्राप्त किया गया है।

परिवर्तनीय परिचालन स्थितियों और जटिल मॉडलिंग को संबोधित करने के लिए इनपुट-आउटपुट संरचना के साथ अडाप्टिव नियंत्रकों का प्रस्ताव किया गया है। थीसिस में कई अडाप्टिव नियंत्रक डिज़ाइन प्रस्तावित हैं, जैसे की मॉडल रेफ्रेन्स अडाप्टिव नियंत्रक - प्रोपोरशनल इंटीग्रल, स्वसेल्फ टोनिंग नियंत्रक, मॉडल-फ्री अडाप्टिव नियंत्रक, और रोबस्ट मॉडल मॉडल रेफ्रेन्स अडाप्टिव नियंत्रक।

फीडबैक सिग्नल में नेटवर्क विलंबता का विश्लेषण किया गया है, और अडाप्टिव नियंत्रक के प्रदर्शन पर उनके प्रभाव पर चर्चा की जाती है। एक नया विलंब क्षतिपूर्तिकर्ता प्रस्तावित किया गया है, जिसमें कई प्रकार के नेटवर्क विलंबता की क्षतिपूर्ति को दर्शाया गया है। इसके अलावा, डायनामिक लीनियरराइज़ेशन के आधार पर एक नया पैकेज ड्रॉप क्षतिपूर्तिकर्ता प्रस्तावित किया गया है।

नियंत्रण संकेतों के क्रियान्वयन के लिए सोलर पावर प्लांट और सिंक्रोनस जनरेटर के एक्ससिटेशन नियंत्रक का उपयोग किया गया है। यह देखा गया है कि सोलर पावर प्लांट से उपयुक्त लौ फ्रीक्वेंसी पावर ओस्किल्लाशंस को दबाया जा सका। सीमित सक्रियण प्रयास को प्राप्त करने के लिए एक रोबस्ट मॉडल मॉडल रेफ्रेन्स अडाप्टिव नियंत्रक का उपयोग किया गया है।

प्रस्तावित पद्धतियों के साथ कठोर केस अध्ययन किए गए और देखा गया कि महत्वपूर्ण लाभ प्राप्त हुए हैं, खासकर अनिश्चितताओं के तहत।

Contents

Certificate	i
Acknowledgements	ii
Abstract	iii
सारांश	iv
Contents	v
List of Figures	xi
List of Tables	xv
Abbreviations	xvii
Symbols	xxi
1 Introduction	1
1.1 Background and Motivation	1
1.2 Low-Frequency Oscillations Problem	3
1.2.1 Power System Stability	3
1.2.2 Small Signal Stability	4
1.2.2.1 Physics Perspective	5
1.2.2.2 Mathematical Perspective	6
1.3 Oscillation Damping Controller	7
1.4 Closed-Loop Blocks in WADC	8
1.4.1 Modeling of Renewable Integrated Power Grid	9
1.4.1.1 Literature Review on Modeling Aspect	12
Modeling of Power System:	12

	Model Order Reduction of IBR's State-Space Model:	12
	Model Free Approach for Power System:	13
1.4.1.2	Research Motivation	14
	Modeling of Inverter Dominated Grid:	14
	Model Free Approach for Power System:	14
1.4.2	Controller	15
1.4.2.1	Literature review	17
1.4.2.2	Research Motivation	18
1.4.3	Feedback	19
1.4.3.1	Literature review	20
	Time Delay Compensation:	20
	Package-Drop Compensation:	21
1.4.3.2	Research Motivation	21
	Time Delay Compensation:	21
	Package-Drop Compensation:	22
1.4.4	Actuator	22
1.4.4.1	Literature review	23
1.4.4.2	Research Motivation	24
1.5	Research Objectives	24
1.6	Summary of Research Work	25
1.6.1	Robust Model Order Reduction	25
1.6.2	Adaptive Wide Area Damping Controller	26
1.6.3	Variable Delay and Package Drop Compensation	27
1.6.4	PV based Power Oscillation Damping	28
1.7	Outcome of the Research	28
1.8	Outline of the Thesis	29
1.8.1	Chapter 1: Introduction	29
1.8.2	Chapter 2: Robust Model Order Reduction	29
1.8.3	Chapter 3: Adaptive Wide Area Damping Controller	30
1.8.4	Chapter 4: Variable Delay and Package Drop Compensation	30
1.8.5	Chapter 5: PV based Power Oscillation Damping	30
1.8.6	Chapter 6: Conclusion and Future Scope	30
2	Robust Model Order Reduction	31
2.1	Introduction	31
2.2	Model Order Reduction of an Interconnected IBMG System	33
2.2.1	System Description of an IBMG	34
2.2.2	Timescale Separations and SPS Form of IBMG	36
2.2.3	IBMG Model Order Reduction	40
2.2.4	Mapping Between Reduced-Order Models of IBMGs	41

2.2.5	Discrepancy between Reduced-Order and Full-Order IBMG Models under Uncertainties	44
2.3	SPS and its Quantitative Analysis	46
2.3.1	Description of SPS	46
2.3.2	Contraction and Partial Contraction	48
2.3.3	Convergence Analysis of SPS	49
2.3.4	Convergence Analysis of SPS Under Modeling Uncertainties	53
2.3.4.1	Uncertainties in z -subsystem	53
2.3.4.2	Uncertainties in the x -subsystem	56
2.3.5	A Linear System Case	59
2.4	Convergence Analysis in the IBMG System	60
2.4.1	Uncertain Cases in IBMG	60
2.4.1.1	Case 1: Uncertainty in SPP Parameters	60
2.4.1.2	Case 2: Robustness to Modeling Uncertainty	63
	Modeling Uncertainties in z -dynamics	63
	Modeling Uncertainty in x -dynamics	64
2.4.2	Different Perturbation Conditions	64
2.4.3	Different Loading Conditions	66
2.4.4	Reduced Order IBMG Model in Interconnected Scenario	67
2.5	Summary	70
3	Adaptive Wide Area Damping Controller	73
3.1	Introduction	73
3.2	Inter-area Oscillation	75
3.3	WADC Input and Output Signal Selection	76
3.4	Adaptive Wide Area Damping Control	77
3.4.1	STC Theory	77
3.4.2	STC Application as WADC	79
3.4.3	Synthesis of MRAC-PI	82
3.4.4	Adaptive-PID	88
3.5	Results and discussion	89
3.5.1	Case: Comparison of Adaptive Control Techniques	89
3.5.2	Case: Verification of Controller Adaptive Property	93
3.5.2.1	a) Variable operating conditions/points	93
3.5.2.2	b) Variable network topology	95
	Scenario I: Testing under network change in the renewable integrated IEEE 11 bus, 4 machine test system.	96
	Scenario II: Testing under network change to IEEE 39 bus, 10 machine test system.	96
3.5.3	Case: Effect of delay in feedback	99

3.6	Summary	100
4	Variable Delay and Package Drop Compensation	103
4.1	Introduction	103
4.2	MFA-WADC for RES integrated Power System	105
4.2.1	Dynamic Linearization	106
4.2.2	PPD Estimation	107
4.2.3	MFA-WADC	108
4.2.4	Effect of Delay and Package Drop on MFA-WADC	109
4.2.4.1	Effect of Delay	110
4.2.4.2	Effect of Package Drop	110
4.3	Compensations of the Wide Area Signal	111
4.3.1	Network Latency	111
4.3.2	Proposed A-PoDC	112
4.3.2.1	Compensation: Variation Around the Mean	112
4.3.2.2	Compensation: Large deviation of Mean	114
4.3.3	Proposed DL-PPD	116
4.4	Results and Discussion	119
4.4.1	Case 1: Variable operating conditions	119
4.4.2	Case 2: Variable Time-delay in Communication Channel	124
	Scenario 1:	124
	Scenario 2:	125
	Scenario 3:	126
4.4.3	Case 3: Package Drop	128
	DD Case 1:	131
	DD Case 2:	132
4.5	Summary	134
5	PV based Power Oscillation Damping	137
5.1	Introduction	137
5.2	Analysis on PV plant displacing synchronous generator	139
5.2.1	POD	140
5.3	Robust-MRAC for POD	141
5.3.1	Generalized Power System Model for WADC	142
5.3.2	Design Framework for R-MRAC	144
5.3.2.1	Defining Controller Structure	144
5.3.2.2	Adaptation Laws	146
5.3.2.3	Modification of Adaptation Laws	148
	Robustness against Uncertainties	148
	Robustness against Disturbance	149
5.3.3	Design of Reference Model	150
5.4	Simulation and Results	151

5.4.1	Power modulation and excitation control comparison	152
5.4.2	R-MRAC Comparison with MRAC-PI	154
5.4.3	Effectiveness of R-MRAC in variable operating conditions	156
5.5	Summary	158
6	Conclusions and Future Work	161
6.1	Summary of the Work	161
6.2	Scope of Future Research	166
A	Robust Model Order Reduction	167
A.1	Elements of the IBMG State Matrix	167
A.2	Elements of MMGs Dynamics (2.8)	169
A.3	Nominal Values of IBMG Parameters	170
A.4	Proof of <i>Lemma 2.3</i> :	171
B	Variable Delay and Package Drop Compensation	173
B.1	Proof of Lemma 4.2	173
B.2	Proof of Theorem 4.3	175
C	PV based Power Oscillation Damping	177
C.1	Proof of Bounded Input Bounded Output Stability	177
	Bibliography	179
	List of Publications	213
	Bio-Data	215

List of Figures

1.1	The Western Inter-connection power system event of 10th August 1996 a) Original system oscillation in COI, b) Simulated response of the event, c) Damping of oscillation by PSS, d) Western Interconnection system's eigenvalues under undamped and damped conditions.	2
1.2	IEEE Classification of power system stability.	4
1.3	closed-loop of a controlled system	7
1.4	closed-loop of a controlled system	8
1.5	Modeling classifications.	10
1.6	Controller classifications.	16
1.7	Issues in the feedback signals and their compensations.	19
1.8	Different types of WADC actuators.	23
2.1	Schematic diagram of an interconnected IBMG system.	35
2.2	Eigenvalue plot for the IBMG#1 a) Eigenvalue of IBMG#1 showing multiple time scales b) Eigenvalue in the range of -10^6 to -2^6 c) Eigenvalue in the range of -3000 to -1000 and d) Eigenvalue in the range of -120 to 0	37
2.3	Algorithm for model order reduction in multi-time scale system.	39
2.4	Reduced order and corresponding full order system state trajectories for a) ΔP b) ΔQ c) $\Delta \phi$ and d) $\Delta \delta$ for all inverters.	41
2.5	a) States trajectories error between full-order and reduced-order models b) percentage relative error between the states after $t \geq 3msec$	42

2.6	Effect of uncertainty in the L_f parameter of IBMG on the discrepancy between the reduced-order model obtained using SP based reduction and the full-order system.	45
2.7	Effect of uncertainty in L_f parameter of IBMG on the discrepancy between the reduced-order model and the full-order system a) Reduced-order model obtained using Hankel model reduction b) Reduced-order model obtained using Balanced stochastic model truncation.	46
2.8	The plot of discrepancy showing that when the given condition (2.20) is satisfied, then convergence occurs a) for ϵ_1 with uncertainty in L_c b) for ϵ_1 with uncertainty in L_{line1} c) for ϵ_2 with uncertainty in L_f and K_{pc} d) for ϵ_2 with uncertainty in C_f and K_{iv}	62
2.9	Discrepancy behavior for modeling uncertainty in z-dynamics (Δ_2) a) The bounds on the parameter C_f decrease with uncertainty $\Delta_2 = 10 \times [\phi_{21}, \phi_{22}]$ b) The new bound on parameter C_f is 0.0076F.	65
2.10	Discrepancy behavior for modeling uncertainty in x-dynamics (Δ_1).	65
2.11	Plot of the relative discrepancy between the reduced-order model and nonlinear full-order IBMG system for different perturbations from its initial condition.	66
2.12	Plot of the discrepancy between the reduced-order model and full-order IBMG system for different operating conditions. . . .	66
2.13	Schematic diagram of the test interconnected system.	67
2.14	Real and reactive power states trajectories for the full-order and the corresponding reduced-order model in the interconnected system a) ΔP_1 for IBMG1 b) ΔP_2 for IBMG1 c) ΔP_3 for IBMG1 d) ΔQ_1 for IBMG1 e) ΔQ_2 for IBMG1 f) ΔQ_3 for IBMG1 g) ΔP_1 for IBMG2 h) ΔP_2 for IBMG2 i) ΔQ_1 for IBMG2 j) ΔQ_2 for IBMG2.	69
3.1	Schematic diagram of STC.	82
3.2	Schematic diagram of MRAC-PI.	88
3.3	Renewable integrated IEEE 2-area test power system.	90
3.4	Speed deviation response with Adaptive WADCs.	91
3.5	Real-time tuning of System parameter estimation.	91
3.6	Real-time tuning of STC gains tuning.	91

3.7	Real-time tuning of MRAC-PI gains tuning.	92
3.8	Real-time tuning of A-PID gains tuning.	92
3.9	Control efforts in MRAC-PI and STC.	92
3.10	Spread of eigenvalues for different operating conditions.	94
3.11	MRAC-PI WADC in variable operating condition.	95
3.12	STC WADC in variable operating condition.	95
3.13	Adaptive control in a change of network topology due to line outage.	96
3.14	IEEE New England Test system	97
3.15	Speed deviation response with adaptive WADC in New England test system.	98
3.16	Impact of delay in Adaptive WADC of a) 50 milliseconds, b) 100 milliseconds, c) 200 milliseconds.	99
4.1	Schematic diagram of the proposed WADC scheme for renewable-power system.	106
4.2	Schematic diagram of network latency.	112
4.3	(a) PDF distribution with zero mean (b) Schematic representation of delay and Po-VCs in terms of vector diagram and their weighted additions.	114
4.4	PV integrated New England Test system.	119
4.5	Speed deviation responses for OP 1.	120
4.6	Speed deviation responses for OP 2.	121
4.7	The PPD parameters online tuning for (a) WADC 1, (b) WADC 2, (c) WADC 3.	122
4.8	(a) Delay profile (b) Online beta tuning.	123
4.9	Speed deviation response under large deviations in time delay, with and without delay compensators.	125
4.10	Delay compensator outputs for the large continuous delay variation.	126

4.11 The non-delayed, delayed, ADC compensated, and A-PoDC compensated signals ($\sigma^2 = 0.01$).	127
4.12 Non-normal PDF and the corresponding area coverage	128
4.13 The non-delayed, delayed, and ADC compensated signals for non-normal delay variation.	129
4.14 The non-delayed, delayed, A-PoDC compensated signals for non-normal delay variation.	130
4.15 Considered package drop patterns.	131
4.16 The package drop and compensated signals for DD Case 1.	132
4.17 The speed deviation responses under DD Case 1.	133
4.18 The package drop and compensated signals for DD Case 2.	134
4.19 The speed deviation responses under DD Case 2.	135
5.3 POD scheme in renewable integrated power system.	139
5.1 PV plant displacing synchronous generator a) Area 1 b) Area 2.	140
5.2 Speed deviation response for PV displacing SG.	140
5.4 Speed deviation with power modulation control and excitation control.	141
5.5 Renewable integrated IEEE 39 bus power system.	152
5.6 Power modulation signal from PV plants.	152
5.7 Comparative response with excitation control and power modulation control.	153
5.8 Comparative response with MRAC-PI and R-MRAC as POD.	154
5.9 Comparison of actuation signals between MRAC-PI and R-MRAC.	155
5.10 Eigen value variation for different operating conditions.	157
5.11 Response in all OPs and power modulation control.	157
5.12 Adaptive gain tuning of ρ for OP5.	158
5.13 Adaptive gain tuning of θ for OP5.	158

List of Tables

2.1	PARAMETERS THAT DEFINE SPP	38
2.2	UPPER BOUNDS OF PARAMETER UNCERTAINTY BEYOND WHICH (2.20) FAILS TO HOLD	61
2.3	UPPER BOUND OF PARAMETER UNCERTAINTY SUCH THAT THE DISCREPANCY IS LESS THAN 10%	63
3.1	DIFFERENT OPERATING POINT (OP)	94
3.2	MODE 1 FREQ. AND DAMPING RATIO	95
3.3	LEAST DAMPED ELECTROMECHANICAL MODES IN NEW ENG- LAND SYSTEM	97
5.1	OPERATING CONDITIONS (OP)	156
A.1	Inverter Parameters Nominal value (P_0)	170
A.2	Network Parameters	170
A.3	Load Parameters	170

Abbreviations

ADC	A daptive D elay C ompensator
A-PID	A daptive P roportional I ntegral D erivative
A-PoDC	A daptive- P robabilistic D elay C ompensator
ARMAX	A uto R egressive M oving A verage with e xogenous inputs
ATDC	A daptive T ime D elay C ompensator
AVR	A utomatic V oltage R egulation
COI	C alifornia O regon I ntertie
C-WADC	C onventional- W ide A rea D amping C ontrol
CAISO	C alifornia I ndependent S ystem O perator
CARMA	C ontinuous T ime A uto- R egressive M oving A verage
CDC	C onstant D elay C ompensator
CIG	C onverter I nterfaced G enerator
DL	D ynamic L inearization
DL-PPD	D ynamic L inearization P seudo P artial D erivative
EM	E lectro M echanical
EPRI	E lectric P ower R esearch I nstitute
ETMSP	E xtended T ransient M idterm S tability P rogram
FACTS	F lexible A lternating C urrent T ransmission S ystem
GPS	G lobal P ositioning S ystem
GPC	G eneralized P redictive C ontroller
Gs	G nerators
GZPG	G uizhou P ower G rid
HVDC	H igh V oltage D irect C urrent
Hz	H ertz
IEEE	I nstitute of E lectrical and E lectronics E ngineers
IBR	I nverter- B ased R esource

IBMG	I nverter- B ased M icro G rid
IBDG	I nverter- B ased D istributed G enerator
LTI	L inear T ime I nvariant
LMI	L inear M atrix I nequality
LQG	L inear Q uadratic G aussian
LQG	L inear Q uadratic R egulator
MOR	M odel O der R eduction
MRAC	M odel R eference A daptive C ontrol
MFA	M odel F ree A daptive
MMG	M ulti- M icro G rid
MMG	M ulti- M icro G rid
MW	M ega- W att
NARX	N onlinear A uto- R egressive with e xogenous inputs
NAR	N onlinear A uto r egressive
OC	O perating C ase
OP	O perating P oint
PDC	P hasor D ata C oncentrator
PSS	P ower S ystem S tabilizer
PPD	P seudo P artial D erivative
PMU	P hasor M easurement U nits
POD	P ower O scillation D amping
PV	P hoto V oltaic
PI	P roportional I ntegral
Po-C	P robabilistic- C ompensator
Po-VC	V ertex P robabilistic- C ompensator
PPC	P ower P lant C ontroller
RES	R enewable E nergy S ources
RLS	R ecursive L east S quare
R-MRAC	R obust MRAC
Ro-COF	R ate o f C hange o f F requency
SP	S ingular P erturbation
SPP	S ingular P erturbation P arameter
SPS	S ingularly P erturbed S ystem
STC	S elf T uning C ontrol
SCADA	S upervisory C ontrol and D ata A cquisition

SG	S ynchronous G enerators
TCSC	T hystistor- C ontrolled S eries C ompensation
USP	U nified S mith P redictor
UKF	U nscented K alman F ilter
UTC	C oordinated U niversal T ime
VDC	V ertex D elay C ompensator
WAMS	W ide A rea M easurement S ystem
WADC	W ide- A rea D amping C ontrol
WECC	W estern E lectricity C oordinating C ouncil

Symbols

ϵ	Singular Perturbation Parameter
μ -WADC	Mu Synthesis WADC
#	number
Δ	perturbed term (Can represent perturbed linear system or uncertainty)
$\rightarrow$	moving towards
$\Rightarrow$	implies that
ω	angular frequency
$\forall$	for all
$\exists$	there exists at least one
$ \cdot $	first norm
$\ \cdot\ $	second norm
$\mathbb{R}^+$	Positive real number
$\mathbb{R}^{n \times m}$	Matrix of size $n \times m$
$\in$	belongs to
$\sim$	is similar to
$\approx$	is approximately
sgn	is sign of