# Department of Electrical and Computer Engineering ECE 792-063 Modeling and Digital Control of Power Electronic Converters

# **Course Overview**

Modeling fundamentals of pulse-width modulation (PWM)-, phase-shift-, and frequencycontrolled power conversion; transforming analog control design to discrete-time implementation; principles of time-scale separated cascaded controllers; linear, hysteretic, hybrid hysteretic, and predictive controllers; small-signal vs large-signal analysis and verification; software-in-the-loop (SIL)/ digital twin modelling; grid-following (GFL) and grid-forming (GFM) control; droop and virtual oscillator controls; voltage source converter controls and controller implementations.

Instructor: Dr. Iqbal Husain & Dr. M A Awal Office: 100 Keystone Rm. 19, Tel: (919)-513-5927 Office Hours: TBD Email: ihusain2@ncsu.edu, mawal@ncsu.edu

Pre-requisites: ECE 534 or equivalent

**Teaching Assistant:** To be assigned Office Hours: TBD

Lecture Schedule: Tue-Thur 4:30-5:45PM

Classroom: EB2 1220

Lectures and Assignments: Lectures will be presented in-person in class. Annotated lecture notes will be posted in Moodle. Homeworks and projects will also be assigned through Moodle.

Recommended Text books: 1. TBD Reference books 1. TBD

### **Modeling Projects:**

Power electronics modeling, digital control, and simulation projects to be developed with computer simulation tools will be assigned related to the topics covered in the course. Matlab-Simulink will be the primary platform for the simulations. The assignments will be collected and graded.

### Homeworks

Homeworks will be assigned to aid the learning and in support of the lecture presentations. In addition to numerical problem solving, homeworks will include computer simulation problems to help prepare for the modeling projects. Homework assignments will need to be submitted online.

# **Drop Deadlines**

Confirm the last day to drop ECE792 from the University Calendar. Lack of prerequisites is not grounds for dropping a course after the deadline.

### **Policy on Absences**

Unexcused absences from exams, homework, or final exam will receive a grade of zero. Makeup exams will not be given except under extenuating circumstances.

### **Grading and Assignments**

The letter grade will be on a 90, 80, 70, 60 scale. Within this range +/- will be used. Grading questions arising as a result of a particular test or exam must be resolved within one week after that test or exam is returned.

#### **Course Contents:**

Pulse-width, phase-shift, and frequency- controlled power conversion Transforming analog control design to discrete-time implementation Principles of time-scale separated cascaded controllers Linear, hysteretic, hybrid hysteretic, and predictive controllers Small-signal vs large-signal analysis and verification Software-in-the-loop (SIL)/ digital twin modelling Grid-following (GFL) and grid-forming (GFM) control Droop and virtual oscillator controls

### Additional Health Measures and Guidelines due to the Coronavirus Pandemic

Due to the Coronavirus pandemic, public health measures have been implemented across campus. Students should stay current with these practices and expectations through the <u>Protect</u> <u>the Pack</u> website (https://www.ncsu.edu/coronavirus/).

Component	Weight	Details	
Homework	25%	Seven to eight homework assignments are assigned during the semester.	
Simulation Projects	50%	Two-three digital control & simulation projects will be assigned. The students submit completed Matlab/Simulink programs and reports.	
Final Exam	25%	A comprehensive final exam is administered at the end of the semester.	

### Grading:

Lec #	Торіс	Assignments
(75	·F ·	
mins.		
each)		
1	Pulse-Width, Phase-Shift, and Frequency Modulated Power Conversion -	
	<ul> <li>Introducing different types of conversion to be covered in the</li> </ul>	
	course	
	• Introduction to different application domains: industrial,	
	automotive, renewable energy	
2	A 2L Phase-Leg: DC-DC & DC-AC operation	#1 Voltage source
	• Identical small-signal model output voltage and current using LC	inverter analysis with
	filter in open-loop for DC and AC outputs	average model
	• Current-control (DC sources on both input and output); PI and PR	
1	compensators for DC and AC current control	
4	Simulation and Implementation Reference Frames	
	• dq transformations for three-phase and single-phase	
	• $\alpha$ - $\beta$ -0 reference frame	
5	Digital/Discrete-Time Control Implementation	#2: design, discretize,
	Analog to digital transformation	& compare freq.
	Modeling digital controllers for analysis & simulation	responses of PR
	Small-signal response verification	current con.
6	Cascaded Control Structure	
	Output voltage control (DC-DC)	
	DC bus voltage control (DC-DC operation)	
7	Design for Worst-Case: Part I	
	Constant-impedance and constant-power loads	
8	Limits of active control: beyond-switching-frequency resonances	#2. J:
8	Single-Phase & Three-Phase Voltage Source Inverter (VSI)	#3: design & simulate voltage controller for
	Unipolar vs bipolar modulation     Three wire four wire systems	constant-P load
	<ul> <li>Three-wire vs four-wire systems</li> <li>Differential-mode (DM) &amp; common-mode (CM) circuits</li> </ul>	constant-1 load
	<ul> <li>Extending output voltage range using CM</li> </ul>	
	Grid-Following (GFL) Inverters	
9	Control structure (DC bus control)	
,	<ul> <li>Phasors vs space vectors</li> </ul>	
	<ul> <li>Stationary and synchronous reference frames</li> </ul>	
	<ul> <li>Phase-locked loop (PLL)</li> </ul>	
	• Double-synchronous PLL	
10	Differential Mode (DM) Filtering: Part I	
_	• DM filter design	
	• Resonance damping – passive and active damping	
	Filter based active damping	
11	Differential Mode (DM) Filtering: Part II	#4: Design DM filter
	• State estimator/observer based active damping	and active damping;
		simulate current
		control in 3phase VSI
12	Common Mode (CM) Filtering	
	• AC & DC CM filters for $3\phi$ VSI	
	• CM chokes	
	• Generalized $3\phi$ choke modeling & testing	
13	GFL VSI Applications in Industrial motor drives, UPS	
	• Active front-end (AFE) in POL application (industrial drives, UPS)	

Image: constraint of the second sec			
• Maximum power point (MPP) tracking for PVs           Term Project I: Three-Phase VSI Simulation Assignment (in Matlab-Simulink): Control design and simulation of 3¢ PV VSI with MPP tracking           15         Digital Twin/Software-in-the-Loop (SIL) Simulation • Introduction • Code segmentation • Multi-rate control         #5: Digital code & SIL simulation: Part II           16         SIL Simulation: Part II • Coding & SIL Demo • Predetak: interaction between systems • Middlebrook's Extra Element Theorem (EET) • Impedance-based stability orticria • Frequency-domain passivity         #5: Digital code & synchronous DC-DC (buck) converter           18         Model-Predictive Control: Part I • Fundamentals of model predictive control (MPC) • Predictive current control • Application Example: ??         #6: Digital code & SIL model of a 3¢ VSI with current controller (PQ reference tracking)           20         Large-Signal/Transient Stability Analysis • Introduction • Transient stability analysis of a three-phase VSI • Analysis of Complex transfer functions • Small-signal analysis of 2L dynamics • Complex transfer functions • Small-signal analysis of 1L dynamics • Complex transfer functions • Small-signal analysis of 2I dynamics • Complex transfer functions • Small-signal analysis of 1L dynamics • Complex transfer function for CHBs • Modulation in Multi-Level Topologies • 31. DNPC modulation with neutral-point voltage balancing • Multi-level Topologies • 31. DNPC modulation in heutral-point voltage balancing • Multi-level Topologies • 31. DNPC modulation with neut	14	GFL VSI Applications in BESS, MPP for PVs	
Term Project I: Three-Phase VSI Simulation of 3\$\$ PV VSI with MPP tracking         15       Digital Twin/Software-in-the-Loop (SIL) Simulation		• Battery energy storage systems (BESS)	
simulation of 3\$\$pt PV VSI with MPP tracking           15         Digital Twin/Software-in-the-Loop (SIL) Simulation <ul></ul>		• Maximum power point (MPP) tracking for PVs	
15       Digital Twin/Software-in-the-Loop (SIL) Simulation         15       Digital Twin/Software-in-the-Loop (SIL) Simulation         16       SIL Simulation: Part II         16       SIL Simulation: Part II         17       Design for Worst-Case: Part II         18       Model-bredictive Control         17       Design for Worst-Case: Part II         18       Feedback interaction between systems         19       Model-Predictive Control: Part I         19       Fundamentals of model predictive control (MPC)         19       Model-Predictive Control: Part II         10       Finite control set (FCS) MPC         20       Large-Signal/Transient Stability Analysis         21       Analysis of Cross-Coupled Dynamics         22       Introduction         23       Modulation in Multi-Level Topologies         24       LLC Resonant Converter: Part II         25       LLC Resonant Converter: Part II         24       ULC Resonant Converter: Part II         25       LLC Resonant Converter: Part II	Tern	•	k): Control design and
Introduction       Introduction         Code segmentation       Multi-ate control         I6       SIL Simulation: Part II       #5: Digital code & SIL model of a synchronous DC-DC (buck) converter         17       Design for Worst-Case: Part II       Feedback interaction between systems         18       Model-Predictive Control: Part II       Feedback interaction between systems         18       Model-Predictive Control: Part I       Feedback interaction passivity         18       Model-Predictive Control: Part II       #6: Digital code & SIL model of a 3p         19       Model-Predictive control: Part II       Finite control set (FCS) MPC         19       Model-Predictive Control: Part II       *6: Digital code & SIL model of a 3p         19       Model-Predictive Control: Part II       *6: Digital code & SIL model of a 3p         19       Model-Predictive Control: Part II       *6: Digital code & SIL model of a 3p         19       Model-Predictive control set (FCS) MPC       SIL model of a 3p         20       Large-Signal/Transient Stability Analysis       #7: Transient stability analysis of a three-phase VSI         21       Analysis of Cross-Coupled Dynamics       #7: Transient stability analysis of PLL dynamics         22       Introduction to Multi-Level Topologies       #7: Transient stability analysis of the VSI         23       Mod		simulation of $3\phi$ PV VSI with MPP tracking	
Introduction       Introduction         Code segmentation       Multi-ate control         I6       SIL Simulation: Part II       #5: Digital code & SIL model of a synchronous DC-DC (buck) converter         17       Design for Worst-Case: Part II       Feedback interaction between systems         18       Model-Predictive Control: Part II       Feedback interaction between systems         18       Model-Predictive Control: Part I       Feedback interaction passivity         18       Model-Predictive Control: Part II       #6: Digital code & SIL model of a 3p         19       Model-Predictive control: Part II       Finite control set (FCS) MPC         19       Model-Predictive Control: Part II       *6: Digital code & SIL model of a 3p         19       Model-Predictive Control: Part II       *6: Digital code & SIL model of a 3p         19       Model-Predictive Control: Part II       *6: Digital code & SIL model of a 3p         19       Model-Predictive control set (FCS) MPC       SIL model of a 3p         20       Large-Signal/Transient Stability Analysis       #7: Transient stability analysis of a three-phase VSI         21       Analysis of Cross-Coupled Dynamics       #7: Transient stability analysis of PLL dynamics         22       Introduction to Multi-Level Topologies       #7: Transient stability analysis of the VSI         23       Mod	15	$D''_{1} + 1T_{2} + 0$ $\theta_{2} + 1$ $\theta_{2} + 1$ $\theta_{2} + 0$ $\theta_{1} + 0$ $\theta_{2} + 1$ $\theta_{1} + 0$	
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• Multi-rate control       #5: Digital code & SIL model of a synchronous DC-DC (buck) converter         16       SIL Simulation: Part II       #5: Digital code & SIL model of a synchronous DC-DC (buck) converter         17       Design for Worst-Case: Part II <ul> <li>Feedback interaction between systems</li> <li>Middlebrook's Extra Element Theorem (EET)</li> <li>Impedance-based stability criteria</li> <li>Frequency-domain passivity</li> <li>8</li> <li>Model-Predictive Control: Part I</li> <li>Fundamentals of model predictive control (MPC)</li> <li>Predictive control: Part II</li> <li>Fundamentals of model predictive control (MPC)</li> <li>Predictive control: Part II</li> <li>Finite control set (FCS) MPC</li> <li>Application Example: ??</li> <li>19</li> <li>Model-Predictive Control: Part II</li> <li>#6: Digital code &amp; SIL model of a 3<math>\phi</math> VSI with current controller (P/Q reference tracking)</li> <li>Introduction</li> <li>Transient Stability Analysis</li> <li>Introduction</li> <li>Small-signal analysis of a three-phase VSI</li> <li>21</li> <li>Analysis of Cross-Coupled Dynamics</li> <li>Complex transfer functions</li> <li>Small-signal analysis of PL dynamics</li> <li>Complex transfer functions</li> <li>Stall-signal analysis of PL dynamics</li> <li>22</li> <li>Introduction to Multi-Level Topologies</li> <li>31. bridge</li> <li>Gascaded H-Bridges (CHB)</li> <li>Modulation in Multi-Level Topologies</li> <li>Multi-level modulation for CHBs</li> <li>LLC Resonant Conve</li></ul>			
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• Coding & SIL Demo       SIL model of a synchronous DC-DC (buck) converter         17       Design for Worst-Case: Part II       • Feedback interaction between systems       • Middlebrook's Extra Element Theorem (EET)         17       Design for Worst-Case: Part II       • Feedback interaction between systems       • Middlebrook's Extra Element Theorem (EET)         18       Model-Predictive Control: Part I       • Frequency-domain passivity       -         18       Model-Predictive Control of model predictive control (MPC)       • Predictive current control         • Application Example: ??       #6: Digital code & SIL model of a 3p         19       Model-Predictive Control : Part II       #6: Digital code & SIL model of a 3p         • Finite control set (FCS) MPC       SIL model of a 3p         • Application Example       * SIL model of a 3p         20       Large-Signal/Transient Stability Analysis       • Introduction         • Introduction       • Transient stability analysis of a three-phase VSI       #7: Transient stability analysis of PLL dynamics         21       Analysis of Cross-Coupled Dynamics       #7: Transient stability analysis of the VSI designed in assignment #6         23       Modulation in Multi-Level Topologies       #7: Transient stability analysis of the VSI designed in assignment #6         23       Modulation in Multi-Level Topologies       • Modulation in Multi-Level Topologies	16		#5: Digital code &
•       synchronous DC-DC (buck) converter         17       Design for Worst-Case: Part II         •       Feedback interaction between systems         •       Middlebrook's Extra Element Theorem (EET)         •       Impedance-based stability criteria         •       Frequency-domain passivity         18       Model-Predictive Control: Part I         •       Fundamentals of model predictive control (MPC)         •       Predictive Control: Part II         •       Finite control set (FCS) MPC         •       Application Example: ??         19       Model-Predictive Control: Part II         •       Finite control set (FCS) MPC         •       Application Example         20       Large-Signal/Transient Stability Analysis         •       Introduction         •       Transient stability analysis of a three-phase VSI         21       Analysis of Cross-Coupled Dynamics         •       Complex transfer functions         •       Small-signal analysis of PLL dynamics         22       Introduction to Multi-Level Topologies         •       Storigge         •       Complex transfer functions         •       Cascaded H-Bridges (CHB)         •       Converter (M	10		ę
17       Design for Worst-Case: Part II <ul> <li>Feedback interaction between systems</li> <li>Middlebrook's Extra Element Theorem (EET)</li> <li>Impedance-based stability criteria</li> <li>Frequency-domain passivity</li> </ul> <ul> <li>Model-Predictive Control: Part I</li> <li>Fundamentals of model predictive control (MPC)</li> <li>Predictive control: Part II</li> <li>Application Example: ??</li> </ul> #6: Digital code & SIL model of a 3φ <ul> <li>VSI with current control</li> <li>Application Example</li> <li>Finite control set (FCS) MPC</li> <li>SIL model of a 3φ             <li>VSI with current controller (P/Q reference tracking)</li> </li></ul> <ul> <li>Introduction</li> <li>Transient Stability Analysis</li> <li>Introduction</li> <li>Small-signal analysis of a three-phase VSI</li> </ul> <ul> <li>Transient stability analysis of a three-phase VSI</li> <li>Complex transfer functions</li> <li>Small-signal analysis of PLL dynamics</li> <li>Complex transfer functions</li> <li>Small-signal analysis of PLL dynamics</li> </ul> #7: Transient stability analysis of the VSI designed in assignment #6              22         Introduction to Multi-Level Topologies          #7: Transient stability analysis of the VSI designed in assignment #6 <li>Modular Multi-level Converter (MMC)</li> <li>Modularion in Multi-Level Topologies</li> <ul> <li>3L DNPC modulation with neutral-point voltage balancing</li>             &lt;</ul>		•	synchronous DC-DC
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• Impedance-based stability criteria       • Frequency-domain passivity         18       Model-Predictive Control: Part I         • Fundamentals of model predictive control (MPC)       • Predictive current control         • Application Example: ??       ************************************		•	
• Frequency-domain passivity       •         18       Model-Predictive Control: Part I         • Fundamentals of model predictive control (MPC)       •         • Predictive current control         • Application Example: ??         19       Model-Predictive Control: Part II         • Finite control set (FCS) MPC       #6: Digital code & SIL model of a 3dy         • Application Example       controller (P/Q)         20       Large-Signal/Transient Stability Analysis         • Introduction       • Transient stability analysis of a three-phase VSI         21       Analysis of Cross-Coupled Dynamics         • Complex transfer functions       *7: Transient stability analysis of PLL dynamics         22       Introduction to Multi-Level Topologies         • Modular Multi-level Converter (MMC)       analysis of the VSI designed in assignment #6         23       Modulation in Multi-Level Topologies         • 3L DNPC modulation with neutral-point voltage balancing       *8: Design a hybrid         • Direct frequency control       *8: Design a hybrid         • Direct frequency control       #8: Design a hybrid         • Direct frequency control       converter			
18       Model-Predictive Control: Part I <ul> <li>Fundamentals of model predictive control (MPC)</li> <li>Predictive current control</li> <li>Application Example: ??</li> </ul> #6: Digital code & SIL model of a 3\$         19       Model-Predictive Control: Part II       #6: Digital code & SIL model of a 3\$         • Finite control set (FCS) MPC       • Application Example       VSI with current controller (P/Q reference tracking)         20       Large-Signal/Transient Stability Analysis       • Introduction       • Transient stability analysis of a three-phase VSI         21       Analysis of Cross-Coupled Dynamics       • Complex transfer functions       • Small-signal analysis of PLL dynamics         22       Introduction to Multi-Level Topologies       #7: Transient stability analysis of the VSI designed in assignment #6         23       Modular Multi-level Topologies       • 3L DNPC modulation with neutral-point voltage balancing       • Multi-level modulation for CHBs         24       LLC Resonant Converter: Part II       • Principle of operation       #8: Design a hybrid hysteretic voltage         25       LLC Resonant Converter: Part II       • Principle of operation       #8: Design a hybrid hysteretic control         26       LLC Resonant Converter: Part II       • Direct frequency control       hybrid hysteretic coltage         26       LLC Resonant Converter: Part II       • Principle of op			
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• Application Example: ??       #6: Digital code &         19       Model-Predictive Control: Part II       #6: Digital code &         • Finite control set (FCS) MPC       SIL model of a 3\$\$         • Application Example       VSI with current controller (P/Q reference tracking)         20       Large-Signal/Transient Stability Analysis       reference tracking)         21       Analysis of Cross-Coupled Dynamics       reference tracking)         21       Analysis of Cross-Coupled Dynamics       #7: Transient stability analysis of a three-phase VSI         21       Analysis of Cross-Coupled Dynamics       #7: Transient stability analysis of PLL dynamics         22       Introduction to Multi-Level Topologies       #7: Transient stability analysis of the VSI designed in assignment #6         22       Introduction to Multi-Level Topologies       assignment #6         23       Modulation in Multi-Level Topologies       #7: Transient stability analysis of the VSI designed in assignment #6         23       Modulation with neutral-point voltage balancing          0       Multi-level Topologies       #8: Design a hybrid hysteretic voltage control hysteretic voltage control hysteretic control         24       LLC Resonant Converter: Part II       #8: Design a hybrid hysteretic control         0       Direct frequency control       hysteretic voltage controller for an LLC converter			
19       Model-Predictive Control: Part II       #6: Digital code & SIL model of a 3\$         • Application Example       VSI with current controller (P/Q reference tracking)         20       Large-Signal/Transient Stability Analysis       • Introduction         • Transient stability analysis of a three-phase VSI       • Complex transfer functions         21       Analysis of Cross-Coupled Dynamics       • Complex transfer functions         • Small-signal analysis of PLL dynamics       #7: Transient stability analysis of the VSI designed in assignment #6         22       Introduction to Multi-Level Topologies       #7: Transient stability analysis of the VSI designed in assignment #6         23       Modulatron in Multi-Level Topologies       • 3L DNPC modulation with neutral-point voltage balancing         24       LLC Resonant Converter: Part I       • Principle of operation         25       LLC Resonant Converter: Part II       #8: Design a hybrid hysteretic control         4       Direct frequency control       #8: Design a hybrid hysteretic control			
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• Application Example       VSI with current controller (P/Q reference tracking)         20       Large-Signal/Transient Stability Analysis       •         21       Analysis of Cross-Coupled Dynamics       •         21       Analysis of Cross-Coupled Dynamics       •         22       Introduction to Multi-Level Topologies       #7: Transient stability analysis of PLL dynamics         22       Introduction to Multi-Level Topologies       #7: Transient stability analysis of the VSI designed in assignment #6         23       Modulat Multi-level Topologies       •         •       •       Modulation in Multi-Level Topologies         •       •       •         •       Modulation in Multi-Level Topologies         •       •       •         •       •       •         •       Modulation in Multi-Level Topologies       •         •       •       •       •         •       Modulation for CHBs       •       •         24       LLC Resonant Converter: Part I       •       *         •       Principle of operation       *       *         25       LLC Resonant Converter: Part II       *       *         •       Direct frequency control       *       * <tr< th=""><td>17</td><td></td><td></td></tr<>	17		
20       Large-Signal/Transient Stability Analysis       controller (P/Q reference tracking)         20       Large-Signal/Transient Stability Analysis       reference tracking)         20       Large-Signal/Transient Stability Analysis of a three-phase VSI       reference tracking)         21       Analysis of Cross-Coupled Dynamics       reference tracking)         22       Introduction to Multi-Level Topologies       #7: Transient stability analysis of PLL dynamics         22       Introduction to Multi-Level Topologies       #7: Transient stability analysis of the VSI designed in assignment #6         23       Modulation in Multi-Level Topologies       assignment #6         23       Modulation for CHBs       reference tracking)         24       LLC Resonant Converter: Part I       #8: Design a hybrid         25       LLC Resonant Converter: Part II       #8: Design a hybrid hysteretic control         26       Hybrid hysteretic control       controller for an LLC converter			
20       Large-Signal/Transient Stability Analysis       Introduction         21       Analysis of Cross-Coupled Dynamics       Introductions         21       Analysis of Cross-Coupled Dynamics       Introduction tansfer functions         22       Introduction to Multi-Level Topologies       #7: Transient stability analysis of the VSI designed in assignment #6         22       Introduction to Multi-Level Topologies       #7: Transient stability analysis of the VSI designed in assignment #6         23       Modulation in Multi-Level Topologies       assignment #6         23       Modulation in Multi-Level Topologies       assignment #6         24       LLC Resonant Converter: Part I       #8: Design a hybrid hysteretic control         25       LLC Resonant Converter: Part II       #8: Design a hybrid hysteretic control			controller (P/Q
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