

# BUILDING ENERGY MANAGEMENT WITH CONTROL OF HVAC AND OTHER FLEXIBLE LOADS

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DEPARTMENT OF ENERGY SCIENCE AND ENGINEERING

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CONTROL OF HVAC AND OTHER FLEXIBLE LOADS**

by

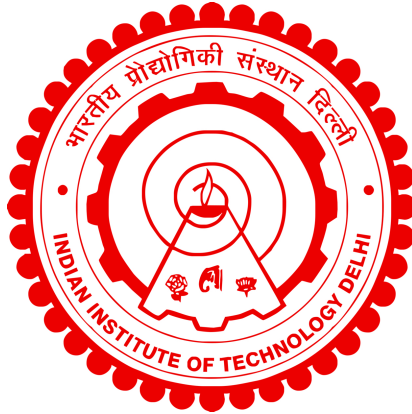
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# Certificate

This is to certify that the thesis entitled “**Building Energy Management with Control of HVAC and Other Flexible Loads**”, submitted by **Mr. Manish Kumar Yadav** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a record of the original, bona fide research work carried out by him under our supervision and guidance. The thesis has reached the standards, fulfilling the requirements of the regulations related to the degree award.

The results in this thesis have not been submitted in part or in full to any other University or Institute for awarding any degree or diploma to the best of my knowledge.

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# *Abstract*

The evolution of conventional power grids into smart grids and integrating smart technologies in buildings present new opportunities for improving energy efficiency. This thesis explores the significance of lighting, Heating Ventilation and Air Conditioning (HVAC) and other flexible loads in buildings, emphasizing the potential for flexibility and controllability. Light-emitting diodes (LEDs) are highlighted for their energy efficiency, focusing on their role in reducing global electricity usage and CO<sub>2</sub> emissions. The first work of the thesis proposes the implementation of lumen control in building lighting systems, incorporating occupant visual comfort as a feedback metric, and introduces a novel retrofitting circuit for standard light fixtures, transforming them into smart, controllable light sources.

Second, HVAC systems are used as virtual ancillary services for power grids. The Air Handling Unit (AHU) fans are controlled by a real-time Internet of Things (IoT) controller based on occupant thermal comfort. Integration of an Adaptive Neuro-Fuzzy Inference System (ANFIS) models the complex relationship between fan torque and required air flow rate to address AHU fan torque non-linearity. Using the proposed algorithm, the case study educational building can achieve ancillary services up to 97 kW during non-scheduled periods and a 20% to 59% increase during scheduled periods. Further, the third part of the thesis proposes a real-time optimum control algorithm for commercial HVAC units to maximise frequency regulation power. Days-ahead HVAC load demand is predicted by the Long Short-Term Memory (LSTM) network. The optimisation algorithm minimises energy costs and thermal discomfort by considering day-ahead electricity tariffs. Hardware prototypes in labs implement the algorithm. It uses a Building Energy Management System (BEMS) and real-time thermal feedback to balance dynamic thermal loads and renewable power.

To transition from one-building to multi-building energy management, this thesis introduces a Modified District Cooling System (MDCS) for building clusters with

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distributed cooling power plants at each building. Different building types' peak cooling power demands for a day are predicted by an LSTM network, affecting their cooling power network capabilities as sellers or buyers. An optimal water piping network layout between seller and buyer nodes is computed using the Grey Wolf Optimisation (GWO) algorithm to minimise cooling power losses and network costs. Case studies show how load forecasting and adaptations to random load increments affect the water distribution network. The Energy Management System (EMS) for this MDCS uses Neural Hierarchical Interpolation for Time-Series Forecasting (N-HiTS) to forecast cooling power load demand hourly. Optimising energy management involves determining the pipe network water pump operating frequency and seller-buyer cooling power-sharing using a metaheuristic algorithm. Optimising a building-cluster cooling plant's operation reduces energy consumption during operation.

As the District Cooling System (DCS) can provide cooling power in large capacity to the cluster of buildings, It could be a potential resource to supply the frequency regulation services to operate the power system smoothly. To provide high-quality regulation services and maximum revenue from the market, accurate forecasting of the building's electrical consumption and sizing of regulation capacity is imperative. Inaccurate sizing of regulation capacity has two major disadvantages: the performance score could be poor, and the building's thermal discomfort may rise. This part of the thesis addresses challenges in optimal sizing regulation capacity for the real-time energy market by DCS. The DCS, thermal storage and EV loads collaborate to maximize revenue through energy-efficient operation. This problem has been formulated and solved using an optimization algorithm. The proposed framework has been simulated, and the results have been presented.

## सार

पारंपरिक पावर ग्रिड का स्मार्ट ग्रिड में विकास और इमारतों में स्मार्ट तकनीकों को एकीकृत करना ऊर्जा दक्षता में सुधार के लिए नए अवसर प्रस्तुत करता है। यह थीसिस इमारतों में प्रकाश व्यवस्था, हीटिंग वेंटिलेशन और एयर कंडीशनिंग (एचवीएसी) और अन्य लचीले भार के महत्व की खोज करती है, लचीलेपन और नियंत्रणीयता की क्षमता पर जोर देती है। प्रकाश उत्सर्जक डायोड (एलईडी) को उनकी ऊर्जा दक्षता के लिए हाइलाइट किया जाता है, जो वैश्विक बिजली के उपयोग और CO<sub>2</sub> उत्सर्जन को कम करने में उनकी भूमिका पर ध्यान केंद्रित करता है। थीसिस का पहला काम इमारत प्रकाश व्यवस्था में लुमेन नियंत्रण के कार्यान्वयन का प्रस्ताव करता है, जिसमें फीडबैक मीट्रिक के रूप में रहने वाले दृश्य आराम को शामिल किया जाता है, और मानक लाइट फिक्स्चर के लिए एक नया रेट्रोफिटिंग सर्किट पेश किया जाता है, जो उन्हें स्मार्ट, नियंत्रणीय प्रकाश स्रोतों में बदल देता है।

दूसरा, एचवीएसी सिस्टम का उपयोग पावर ग्रिड के लिए वर्चुअल सहायक सेवाओं के रूप में किया जाता है। एयर हैंडलिंग यूनिट (एएचयू) पंखे एक वास्तविक समय इंटरनेट ऑफ़ थिंग्स (IoT) नियंत्रक द्वारा नियंत्रित होते हैं जो कि रहने वाले के थर्मल आराम पर आधारित होते हैं। एक अनुकूली न्यूरो-फ़ज़्ज़ी इंफ़रेंस सिस्टम (एएनएफआईएस) का एकीकरण एएचयू फैन टॉर्क गैर-रैखिकता को संबोधित करने के लिए पंखे के टॉर्क और आवश्यक वायु प्रवाह दर के बीच जटिल संबंध को मॉडल करता है। प्रस्तावित एल्गोरिथम का उपयोग करके, केस स्टडी शैक्षणिक भवन गैर-अनुसूचित अवधि के दौरान 97 kW तक की सहायक सेवाएँ प्राप्त कर सकता है और अनुसूचित अवधि के दौरान 20% से 59% की वृद्धि कर सकता है। इसके अलावा, थीसिस का तीसरा भाग वाणिज्यिक एचवीएसी इकाइयों के लिए आवृत्ति विनियमन शक्ति को अधिकतम करने के लिए एक वास्तविक समय इष्टतम नियंत्रण एल्गोरिथम का प्रस्ताव करता है। आने वाले दिनों की एचवीएसी लोड मांग का अनुमान लॉन्ग शॉर्ट-टर्म मेमोरी (एल एस टी एम) नेटवर्क द्वारा लगाया जाता है। अनुकूलन एल्गोरिथम आने वाले दिनों की बिजली दरों पर विचार करके ऊर्जा लागत और थर्मल असुविधा को कम करता है। प्रयोगशालाओं में हार्डवेयर प्रोटोटाइप एल्गोरिथम को लागू करते हैं। यह गतिशील तापीय भार और नवीकरणीय ऊर्जा के बीच संतुलन बनाने के लिए भवन ऊर्जा प्रबंधन प्रणाली (बीईएमएस) और वास्तविक समय तापीय फीडबैक का उपयोग करता है।

एक-इमारत से बहु-इमारत ऊर्जा प्रबंधन में संक्रमण के लिए, यह थीसिस प्रत्येक इमारत में वितरित शीतलन बिजली संयंत्रों के साथ इमारत समूहों के लिए एक संशोधित जिला शीतलन प्रणाली (एमडीसीएस) पेश करती है। एक दिन के लिए विभिन्न प्रकार की इमारतों की अधिकतम शीतलन शक्ति की मांग का अनुमान एलएसटीएम नेटवर्क द्वारा लगाया जाता है, जो विक्रेता या खरीदार के रूप में उनकी शीतलन शक्ति नेटवर्क क्षमताओं को प्रभावित करता है। शीतलन शक्ति के नुकसान और नेटवर्क लागत को कम करने के लिए ग्रे वुल्फ ऑप्टिमाइज़ेशन (जीडब्ल्यूओ) एल्गोरिदम का उपयोग करके विक्रेता और खरीदार नोड्स के बीच एक इष्टतम जल पाइपिंग नेटवर्क लेआउट की गणना की जाती है। केस स्टडीज़ दिखाती हैं कि लोड पूर्वानुमान और यादृच्छिक लोड वृद्धि के लिए अनुकूलन जल वितरण नेटवर्क को कैसे प्रभावित करते हैं। इस डी.सी.एस के लिए ऊर्जा प्रबंधन प्रणाली (ईएम) प्रति घंटे शीतलन शक्ति लोड मांग का पूर्वानुमान लगाने के लिए समय-श्रृंखला पूर्वानुमान (एन-हिट्स) के लिए न्यूरल पदानुक्रमित इंटरपोलेशन का उपयोग करती है। ऊर्जा प्रबंधन को अनुकूलित करने में मेटाहेयुरिस्टिक एल्गोरिदम का उपयोग करके पाइप नेटवर्क वॉटर पंप ऑपरेटिंग आवृत्ति और विक्रेता-खरीदार शीतलन शक्ति-साझाकरण निर्धारित करना शामिल है। बिल्डिंग-क्लस्टर कूलिंग प्लांट के संचालन को अनुकूलित करने से संचालन के दौरान ऊर्जा की खपत कम हो जाती है।

चूंकि डिस्ट्रिक्ट कूलिंग सिस्टम (डी.सी.एस) इमारतों के समूह को बड़ी क्षमता में शीतलन ऊर्जा प्रदान कर सकता है, यह बिजली प्रणाली को सुचारू रूप से संचालित करने के लिए आवृत्ति विनियमन सेवाओं की आपूर्ति करने के लिए एक संभावित संसाधन हो सकता है। उच्च-गुणवत्ता वाली विनियमन सेवाएं और बाजार से अधिकतम राजस्व प्रदान करने के लिए, भवन की विद्युत खपत और विनियमन क्षमता के आकार का सटीक पूर्वानुमान अनिवार्य है। विनियमन क्षमता के गलत आकार के दो बड़े नुकसान हैं: प्रदर्शन स्कोर खराब हो सकता है, और भवन की थर्मल असुविधा बढ़ सकती है। थीसिस का यह हिस्सा डी.सी.एस द्वारा वास्तविक समय ऊर्जा बाजार के लिए इष्टतम आकार विनियमन क्षमता में चुनौतियों को संबोधित करता है। डी.सी.एस, थर्मल स्टोरेज और ई.वी लोड ऊर्जा-कुशल संचालन के माध्यम से राजस्व को अधिकतम करने के लिए सहयोग करते हैं।

# Contents

Certificate

Acknowledgements i

Abstract iii

Contents v

List of Figures ix

List of Tables xiii

Abbreviations xv

Symbols xix

**1 Introduction 1**

1.1 Motivation . . . . . 6

1.2 Research Objectives & Major Contributions . . . . . 8

1.3 Thesis Organizations . . . . . 11

**2 Literature Review and Research Gaps 17**

2.1 Control Framework for the Lighting Management System . . . . . 17

2.2 Control Algorithm of Air Handling Unit for the Ancillary Services . . 21

2.3 Real-Time Optimal Multi-Level Control Algorithm for HVAC System 25

2.4 Planning of Peer-to-Peer Thermal Energy Sharing in Buildings . . . . 29

2.5 Optimal Energy Management of DCS and EV to Support the Grid in  
Real-Time Energy Market . . . . . 31

**3 Light Intensity Control of LED Lights and Energy Analysis of  
Lighting Management System 37**

3.1 Introduction . . . . . 37

3.2	Working of DC-DC Converter . . . . .	40
3.2.1	Buck Converter . . . . .	41
3.2.2	Flyback Converter . . . . .	44
3.3	Design and Development Retrofitting Components . . . . .	48
3.3.1	LED Driver ICs . . . . .	48
3.3.2	Design of Variable Resistor . . . . .	49
3.4	Description of the Proposed Control Scheme . . . . .	52
3.4.1	User Visual Feedback . . . . .	55
3.4.2	Communication Infrastructure . . . . .	57
3.4.3	Trans-receiver and Receiver Module . . . . .	60
3.4.4	Lighting Management System . . . . .	61
3.5	Experimental Validation and Result Discussion . . . . .	65
3.5.1	Laboratory Set-up . . . . .	65
3.5.2	Lighting Management System observation . . . . .	67
3.6	Conclusion . . . . .	71
<b>4</b>	<b>Control Framework for HVAC unit to Enhance the Ancillary Power Capacity of a building</b>	<b>73</b>
4.1	Introduction . . . . .	73
4.2	System Modelling . . . . .	78
4.2.1	R-C modelling of thermal zone . . . . .	78
4.2.2	AHU Fan Modelling . . . . .	82
4.2.3	Adaptive Neuro Fuzzy Inference System . . . . .	84
4.3	Function of Proposed Controlling Scheme . . . . .	86
4.3.1	TCP/IP communication . . . . .	86
4.3.2	Occupancy Estimation . . . . .	86
4.3.3	Occupants feedback system . . . . .	87
4.4	Description of Proposed System . . . . .	88
4.4.1	Overall system . . . . .	88
4.4.2	Reserve Scheduling according to classroom schedule . . . . .	90
4.4.3	Controlling of AHU . . . . .	92
4.4.4	Laboratory Scaled Experimental Set-up . . . . .	94
4.4.4.1	VFD Control System . . . . .	96
4.5	Experimental Results and Discussion . . . . .	96
4.5.1	Ancillary potential at normal scheduling . . . . .	96
4.5.2	Results of experimental set-up . . . . .	97
4.6	Conclusion . . . . .	101
<b>5</b>	<b>Multilevel Control Algorithm for Energy-Efficient Operation of HVAC System</b>	<b>103</b>
5.1	Introduction . . . . .	103
5.2	System Modelling . . . . .	108

5.2.1	Hour-Ahead forecasting of Cooling load . . . . .	108
5.2.2	HVAC system modeling . . . . .	110
5.2.3	Thermal preference of occupants . . . . .	116
5.2.4	Required cooling load . . . . .	118
5.3	Problem Formulation . . . . .	119
5.3.1	Objective function . . . . .	119
5.3.2	Solar power generation . . . . .	120
5.3.3	Cost function . . . . .	121
5.3.4	Bidding capacity in Energy Market . . . . .	122
5.4	Control Algorithm and Workflow . . . . .	123
5.4.1	Proposed operating scheme for HVAC system . . . . .	123
5.4.2	Control flow of the proposed algorithm . . . . .	124
5.5	Simulation and Experimental Verification . . . . .	127
5.5.1	Simulation . . . . .	127
5.5.2	Laboratory scaled experimental setup . . . . .	131
5.5.3	Experimental Verification . . . . .	133
5.5.3.1	Scenario 1 (Non-optimal PI control of HVAC system)	134
5.5.3.2	Scenario 2 (Optimal PI control of HVAC system)	136
5.5.4	Comparative study . . . . .	139
5.6	Conclusions . . . . .	142
<b>6</b>	<b>Optimal Planning Framework for Modified District Cooling System</b>	<b>145</b>
6.1	Introduction . . . . .	145
6.2	Architecture and Modelling of Modified District Cooling System . . . . .	148
6.2.1	Thermodynamics of modified district cooling system . . . . .	149
6.2.2	Cooling power loss in piping network . . . . .	150
6.2.3	Variable flow control of water pump . . . . .	152
6.2.4	Piping Cost . . . . .	153
6.3	Cooling Load Forecasting . . . . .	154
6.3.1	Long-term Peak Cooling Load Forecasting . . . . .	154
6.3.1.1	Recurrent Neural Network . . . . .	154
6.3.2	Day ahead Cooling Load Forecasting . . . . .	156
6.3.2.1	N-HiTS . . . . .	156
6.4	Planning Optimization Framework . . . . .	159
6.4.1	Problem Objective . . . . .	159
6.4.2	Grey Wolf Optimization . . . . .	160
6.5	Case Studies & Numerical Simulation . . . . .	163
6.5.1	Long Term Thermal load forecasting . . . . .	164
6.5.2	Case 1: Without forecasting . . . . .	164
6.5.3	Case 2: 20 % load increment . . . . .	165
6.5.4	Case 3: With load forecasting . . . . .	167

6.5.5	Short Term Thermal load forecasting . . . . .	168
6.5.6	Optimal operation of MDCS . . . . .	169
6.5.7	Cost analysis . . . . .	171
6.6	Conclusions . . . . .	172
<b>7</b>	<b>Energy Management of District Cooling System to provide Fre-</b>	
	<b>quency Regulation</b> . . . . .	<b>175</b>
7.1	Introduction . . . . .	175
7.2	System Modeling . . . . .	177
7.2.1	District Cooling System and air conditioning zone . . . . .	178
7.2.1.1	Thermodynamics of DCS . . . . .	178
7.2.1.2	Required thermal load of a building . . . . .	179
7.2.2	Regulation Capacity offered in market . . . . .	180
7.3	Online Regulation Capacity Offered by DRL . . . . .	182
7.3.1	Capacity Offering based on MDP . . . . .	182
7.3.1.1	Action . . . . .	183
7.3.1.2	State . . . . .	183
7.3.1.3	Rewards . . . . .	183
7.3.2	Proposed strategy for Capacity Offering . . . . .	184
7.4	Case studies . . . . .	185
7.5	Conclusion . . . . .	187
<b>8</b>	<b>Conclusions and Scope of Future Work</b> . . . . .	<b>189</b>
8.1	Contributions . . . . .	190
8.2	Scope of Future Work . . . . .	192
	<b>Bibliography</b> . . . . .	<b>195</b>
	<b>List of Publications</b> . . . . .	<b>227</b>

# List of Figures

1.1	Layout of smart building and energy market in smart grid scenario. . .	3
1.2	Layout of thesis co-relating the individual chapters. . . . .	12
3.1	Basic circuit diagram of a buck converter. . . . .	42
3.2	Sample commercial buck converter, considered for the experiments. .	42
3.3	Schematic diagram of a commercial buck converter with an LED driver IC (MT7830). . . . .	43
3.4	Basic electrical performance of considered commercial buck converter-based LED driver. . . . .	44
3.5	Basic circuit diagram of a flyback converter. . . . .	45
3.6	Sample commercial flyback converter, considered for the experiments. .	46
3.7	Schematic diagram of a commercial flyback converter with an LED driver IC (MT79325). . . . .	46
3.8	Basic electrical performance of considered commercial flyback converter-based LED driver. . . . .	47
3.9	Package diagram and Internal pin layout of the MT7830 (single-stage buck converter IC). . . . .	49
3.10	Package diagram and Internal pin layout of the MT79325 (single-stage flyback converter IC). . . . .	50
3.11	Layout of the proposed variable resistance. . . . .	50
3.12	Work flow of the controlling of proposed variable resistor. . . . .	51
3.13	Schematic diagram of relay switching control circuit. . . . .	52
3.14	Layout of integration of developed variable resistor with type A IC (MOSFET is connected in peripheral of IC). . . . .	53
3.15	Layout of integration of developed variable resistor with type B IC (MOSFET is inbuilt with IC). . . . .	53
3.16	Functional visualization of the proposed Lighting Management System. .	54
3.17	Layout of developed android application for the user visual feedback. .	56
3.18	Visualization of the cloud-based storage of the user's visual comfort feedback. . . . .	57
3.19	layout of TCP/IP packet format. . . . .	58
3.20	Developed prototype of the transceiver module. . . . .	61
3.21	Work-flow chart of the developed transceiver module. . . . .	61

3.22	Developed prototype of the receiver module. . . . .	62
3.23	Work-flow chart of the developed receiver module. . . . .	62
3.24	Left: An Unplanned sitting arrangement; Right: A planned sitting arrangement in a classroom. . . . .	63
3.25	Laboratory scaled experimental set up of the retrofitting solution-based lighting control system . . . . .	66
3.26	Total Harmonic Distortion analysis of AC side current at various light intensity operation. . . . .	68
3.27	Experimental setup of the lighting management system with one transceiver and three receiver nodes. . . . .	69
4.1	R-C model of air conditioning zone. . . . .	79
4.2	Thermal response of the simulated air conditioning zone in condition one on MATLAB. . . . .	81
4.3	Thermal response of air conditioning zone in condition one on Energy Plus. . . . .	81
4.4	Thermal response of the simulated air conditioning zone in condition two on MATLAB. . . . .	82
4.5	Thermal response of air conditioning zone in condition two on Energy Plus. . . . .	82
4.6	Relation between Fan power consumption and operating frequency . . . . .	83
4.7	Relation between Air flow rate of AHU fan and operating frequency. . . . .	84
4.8	ANFIS training data with training error. . . . .	85
4.9	Format of TCP/IP packet. . . . .	87
4.10	Evaluation of developed system for the occupancy estimation through image processing . . . . .	88
4.11	Developed mobile application for feedback. . . . .	89
4.12	Proposed system architecture. . . . .	90
4.13	Ancillary power available for weekdays of different sizes of room. . . . .	91
4.14	Layout of the AHU installed in LHC if IIT Delhi. . . . .	92
4.15	Layout of the proposed system of Air conditioning system connected with a building with a user feedback system. . . . .	93
4.16	Experimental set-up to validate the proposed system installed in the laboratory . . . . .	95
4.17	Ancillary service provision capacity by AHU network for five weekdays according to the timetable schedule of building. . . . .	97
5.1	Comparison of testing and forecasted data trained of LSTM network. . . . .	110
5.2	Integration of different subsystems of HVAC with BEMS and air-conditioned zone. . . . .	111
5.3	Thermal (R-C) model of the air conditioning zone. . . . .	117
5.4	Thermal preference of occupants inside the air conditional zone. . . . .	118
5.5	Flow of the proposed optimization framework for HVAC control. . . . .	123

5.6	Control flow diagram of the proposed algorithm in different cases. . .	125
5.7	Training and testing of developed ANN for compressor discharge pressure. . . . .	128
5.8	Training and testing of developed ANN for compressor suction pressure. . . . .	128
5.9	Analysis of training and testing of refrigerant property on ANFIS. . .	129
5.10	Performance analysis of modelled HVAC unit and air conditioning zone in MATLAB simulation (a) suction and discharge pressure of compressor model. . . . .	129
5.11	Performance analysis of modelled HVAC unit and air conditioning zone in MATLAB simulation chilled water supply, room air, supply air temperature, and thermal preference of occupants. . . . .	130
5.12	Performance analysis of modelled HVAC unit and air conditioning zone in MATLAB simulation power consumption of the different parts of HVAC unit. . . . .	130
5.13	Implementation of the proposed synchronized hierarchy control of HVAC system following an optimization algorithm on a laboratory-scaled experimental setup. . . . .	132
5.14	Monitoring of chilled water and Room air temperature with their respective set point and operating frequency of different machines in the experimental setup of the HVAC unit during the execution of scenario one considering different cases like case one. . . . .	134
5.15	Monitoring of chilled water and Room air temperature with their respective set point, and operating frequency of different machines in the experimental setup of the HVAC unit during the execution of scenario one considering different cases like case two. . . . .	135
5.16	Monitoring of chilled water and Room air temperature with their respective set point and operating frequency of different machines in the experimental setup of the HVAC unit during the execution of scenario one considering different cases like case three. . . . .	135
5.17	Monitoring of chilled water and Room air temperature with their respective set point and operating frequency of different machines in the experimental setup of the HVAC unit during the execution of scenario one considering different cases like case four. . . . .	135
5.18	Monitoring of the experimental setup during the execution of scenario two in one condition suction and discharge pressure at the compressor end. . . . .	137
5.19	Monitoring of the experimental setup during the execution of scenario two in one condition chilled water and Room air temperature with their respective set point. . . . .	137
5.20	Monitoring of the experimental setup during the execution of scenario two in one condition operating frequency of different machines in the HVAC system. . . . .	138

5.21	Monitoring of the experimental setup during the execution of scenario two in one condition electrical power analysis of the considered system.	138
5.22	Monitoring of the experimental setup during the execution of scenario two in the second condition (a) suction and discharge pressure at the compressor end. . . . .	139
5.23	Monitoring of the experimental setup during the execution of scenario two in the second condition chilled water and Room air temperature with their respective set point. . . . .	139
5.24	Monitoring of the experimental setup during the execution of scenario two in the second condition operating frequency of different machines in the HVAC system. . . . .	140
5.25	Monitoring of the experimental setup during the execution of scenario two in the second condition electrical power analysis of the considered system. . . . .	140
6.1	Architecture of air conditioning zone of considered buildings and their respective geometrical location. . . . .	149
6.2	Illustration of thermal energy balance in cooling water piping network.	151
6.3	Schematic of radial thermal power flow from a multi-layer hollow cylindrical pipe . . . . .	151
6.4	Training and testing of trained LSTM network for the long-term forecasting of the cooling loads of buildings. . . . .	155
6.5	Layout of N-HiTS Architecture. . . . .	157
6.6	Peak cooling load forecasting by LSTM network. . . . .	165
6.7	Water piping network layout in case 1 . . . . .	166
6.8	Water piping network layout in case 2 . . . . .	166
6.9	Water piping network layout in case 3 . . . . .	167
6.10	Day-ahead cooling load forecasting following N-HiTS method. . . . .	168
6.11	Water-piping network layout in of considered building cluster. It also shows the water pipe length between two points. . . . .	169
6.12	Water pipe cost analysis considering different cases. . . . .	172
7.1	Layout of District Cooling System with connected buildings. . . . .	178
7.2	Procedure of regulation services in PJ Market. . . . .	181
7.3	Framework for proposed strategy. . . . .	185
7.4	Marginal price and regulation signal from PJM for one day. . . . .	186

# List of Tables

3.1	Switching logic control to get a required resistance . . . . .	51
3.2	Considered parameters for the calculation of the payback period. . . .	64
3.3	Payback period calculation . . . . .	64
3.4	Numerical analysis of proposed control scheme, validated on a laboratory scaled set up. . . . .	65
3.5	Distance v/s Illuminance calculation . . . . .	69
3.6	Experimental results of various parameters in different modes . . . .	69
3.7	Connected lighting load in the classrooms of considered building . . .	70
3.8	Load profile and load saving . . . . .	71
3.9	Overall payback period . . . . .	71
4.1	Parameters of considered air conditioning zone on MATLAB. . . . .	80
4.2	Parameters of considered air conditioning zone on energy plus. . . . .	81
4.3	Parameter of fan model. . . . .	83
4.4	Load profile and power consumption at 23°C room temperature. . . .	99
4.5	Load profile and power consumption at 24°C room temperature. . . .	99
4.6	Load profile and power consumption at 25°C room temperature. . . .	100
4.7	Load profile and power consumption at 26°C room temperature. . . .	100
5.1	Considered values of constants. . . . .	128
5.2	Constant Parameters of Compressor, condenser, water pump, and AHU.	131
5.3	Power rating of the installed experimental setup of HVAC unit in the laboratory. . . . .	133
5.4	Power analysis and comparison amongst different operating conditions of the HVAC system. . . . .	141
5.5	Energy analysis and comparison between optimal and non-optimal control. . . . .	141
6.1	Capacity of chiller plant installed at each building node (in TR). . . .	148
6.2	Present peak thermal load of the individual building (in TR). . . . .	164
6.3	Forecasted peak load after five years (in TR). . . . .	165
6.4	Seller buyer condition . . . . .	165
6.5	Supply and Demand Cooling Power in case 1 . . . . .	166
6.6	Supply and Demand Cooling Power in case 2 . . . . .	167

*List of Tables*

---

6.7	Supply and Demand Cooling Power in case 3 . . . . .	168
6.8	Considered peak cooling load of each building (in TR). . . . .	169
6.9	Sharing of Thermal power between sender and receiver building at 00:15 operating hr . . . . .	170
6.10	Sharing of Thermal power between sender and receiver building at 00:30 operating hr . . . . .	170
6.11	Sharing of Thermal power between sender and receiver building at 00:45 operating hr . . . . .	171
6.12	Sharing of Thermal power between sender and receiver building at 01:00 operating hr . . . . .	171
6.13	Distance between seller and buyer building . . . . .	171
7.1	Parameter settings of the building cluster. . . . .	186
7.2	Performance score of the system. . . . .	187

# Abbreviations

<b>AC</b>	Alternating Current
<b>ACH</b>	Air Change-rate per Hour
<b>ADAL</b>	Accelerated Distributed Augmented Lagrangian
<b>ADNs</b>	Active Distribution Networks
<b>AHU</b>	Air Handling Unit
<b>AI</b>	Artificial Intelligence
<b>ANFIS</b>	Adaptive Neuro-Fuzzy Inference System
<b>ANN</b>	Artificial Neural Network
<b>BAS</b>	Building Automation System
<b>BEE</b>	Bureau of Energy Efficiency
<b>BEMS</b>	Building Energy Management System
<b>BMS</b>	Building Management System
<b>BPA</b>	Back Propagation Algorithm
<b>CG</b>	Conjugate Gradient
<b>CUF</b>	Capacity Utilization Factor
<b>DC</b>	Direct Current
<b>DCS</b>	District Cooling System
<b>DDPG</b>	Deep Deterministic Policy Gradient
<b>DERs</b>	Distributed Energy Resources
<b>DHC</b>	District Heating and Cooling
<b>DL</b>	Deep Learning
<b>DPs</b>	Dynamic Programming
<b>DP</b>	Discharge Pressure
<b>DRL</b>	Deep Reinforcement Learning
<b>ECBC</b>	Energy Conservation Building Code
<b>EMS</b>	Energy Management System

<b>EVs</b>	Electric Vehicles
<b>FIS</b>	Fuzzy Inference System
<b>FLC</b>	Fuzzy Logic Control
<b>GA</b>	Genetic Algorithm
<b>GRU</b>	Gated Recurrent Unit
<b>GUI</b>	Graphical User Interface
<b>GWO</b>	Grey Wolf Optimization
<b>HTTP</b>	Hypertext Transfer Protocol
<b>HVAC</b>	Heating Ventilation and Air Conditioning
<b>ICs</b>	Integrated Circuits
<b>LDRs</b>	Light Dependent Resistors
<b>LED</b>	Light Emitting Diode
<b>LHC</b>	Lecture Hall Complex
<b>LMS</b>	Lighting Management System
<b>LNA</b>	Low Noise Amplifier
<b>LPW</b>	Lumen Per Watt
<b>LSTM</b>	Long Short-Term Memory
<b>MCU</b>	Micro-controller Unit
<b>MDCS</b>	Modified District Cooling System
<b>MG</b>	MicroGrid
<b>MILP</b>	Mixed Integer Linear Programming
<b>MIMO</b>	Multiple Input Multiple Output
<b>ML</b>	Machine Learning
<b>MLP</b>	Multi Layer Perceptron
<b>MPC</b>	Model Predictive Control
<b>NHiTS</b>	Neural Hierarchical Interpolation for Time-Series Forecasting
<b>NPC</b>	Net Present Cost
<b>nRF</b>	nano Radio Frequency
<b>P2P</b>	Peer-to-Peer
<b>PA</b>	Power Amplifier
<b>PLC</b>	Programmable Logic Control
<b>PMV</b>	Predictive Mean Vote
<b>PSO</b>	Particle Swarm Optimization
<b>PWM</b>	Pulse Width Modulation
<b>RMSE</b>	Root Mean Error Square

## *Abbreviations*

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<b>RNN</b>	Recurrent Neural Network
<b>RPM</b>	Rotation Per Minute
<b>SCADA</b>	Supervisory Control And Data Acquisition
<b>SCG</b>	Scaled Conjugate Gradient
<b>SDP</b>	Semi Definite Programming
<b>SMPC</b>	Stochastic Model Predictive Control
<b>SP</b>	Suction Pressure
<b>TCP/IP</b>	Transmission Control Protocol / Internet Protocol
<b>THD</b>	Total Harmonic Distortion
<b>V2G</b>	Vehicle to Grid
<b>VFD</b>	Variable Frequency Drive



# Symbols

$A_{SPV}$	Area of solar panel
$C_p$	Penalty
$C_z$	Thermal capacitance of air conditioning zone
$df$	Degradation factor
$\eta_{SPV}$	Solar panel efficiency
$\eta_m$	Motor efficiency
$f_{AHU}$	Operating frequency of AHU fan
$f_{comp}$	Operating frequency of compressor
$f_{cond}$	Operating frequency of condenser fan
$f_{pump}$	Operating frequency of water pump
$\dot{M}_{a,s}$	Mass flow rate of supply air
$\dot{M}_{chlr}^t$	Mass flow rate of water in chiller plant at time t
$\dot{M}_{cond}$	Air flow rate in condenser
$\dot{M}_{refri}$	Mass flow rate of refrigerant
$\dot{M}_w$	Mass flow rate of water
$\dot{M}_{zone}$	Mass flow rate of air in zone
$N_r$	Speed of AHU motor in RPM
$P_{AHU}$	Power consumption in AHU
$P_{chlr}^t$	Power consumption of chiller plant at time t
$P_{comp}$	Compressor power consumption
$P_{cond}$	Power consumption by condenser unit
$P_d^t$	Discharge pressure at time t
$P_{fan}$	Power consumption of AHU fan
$P_{grid}^t$	Grid power at time t
$P_{pump}$	Power consumption of water pump
$P_{SPV}^t$	Solar power generation at time t

## List of Symbols

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$P_s^t$	Suction pressure at time t
$\dot{Q}_{AHU}$	Cooling power supplied through AHU
$\dot{Q}_{chlr}^t$	Cooling power supply from chiller plant at time t
$\dot{Q}_{cond}$	Cooling power exchange in condenser
$\dot{Q}_{equipment}$	Thermal loads due to equipment
$\dot{Q}_{HVAC,required}$	Required cooling power from HVAC
$\dot{Q}_{HVAC,supply}$	Cooling power supplied by HVAC
$\dot{Q}_{indoor}$	Thermal load generation inside the zone
$\dot{Q}_{lights}$	Thermal loads due to lights
$\dot{Q}_{loss}$	Radial cooling loss in water piping
$\dot{Q}_{occupants}$	Thermal load due to occupants
$\dot{Q}_{pump}$	Cooling power supplied through water network
$\dot{Q}_{refri,s}$	Cooling power supplied by refrigerant
$\dot{Q}_{zone,r}$	Required cooling power in a zone
$R_{in}$	Thermal resistance of inside
$\rho_{vapour}$	vapour density of refrigerant
$R_W$	Thermal resistance of wall
$T_{atm}$	Atmospheric temperature
$T_{chlr,r}^t$	Return water temperature to chiller plant at time t
$T_{chlr,s}^t$	Supply water temperature from chiller plant at time t
$T_r$	Return air temperature in AHU
$T_s$	Supply air temperature from AHU
$T_{set}$	Set ambient temperature of room
$T_{set,air}$	Temperature of supplied chilled air
$T_{vote}$	Average thermal preference of occupants
$T_w$	Instantaneous temperature of wall
$T_{w,r}$	Return water temperature
$T_{w,s}$	Supplied water temperature
$T_z$	Instantaneous temperature of air conditioning zone
$V_{sup}$	Volumetric rate of supply air
$\vec{x}[n]$	Normalised dataset
$\vec{x}_0[n]$	Training data set