# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER NO.</th>
<th>TITLE</th>
<th>PAGE NO.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td></td>
<td>LIST OF TABLES</td>
<td>XIII</td>
</tr>
<tr>
<td></td>
<td>LIST OF FIGURES</td>
<td>XVI</td>
</tr>
<tr>
<td></td>
<td>LIST OF SYMBOLS AND ABBREVIATIONS</td>
<td>XXII</td>
</tr>
<tr>
<td>1</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1</td>
<td>BRUSHLESS DC MOTOR</td>
<td>1</td>
</tr>
<tr>
<td>1.1.1</td>
<td>Applications with constant loads</td>
<td>1</td>
</tr>
<tr>
<td>1.1.2</td>
<td>Applications with varying loads</td>
<td>2</td>
</tr>
<tr>
<td>1.1.3</td>
<td>Positioning applications</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>LITERATURE REVIEW</td>
<td>3</td>
</tr>
<tr>
<td>1.2.1</td>
<td>Proportional Integral Derivative controller</td>
<td>3</td>
</tr>
<tr>
<td>1.2.2</td>
<td>Fuzzy logic controller</td>
<td>5</td>
</tr>
<tr>
<td>1.2.3</td>
<td>Neural network based controller</td>
<td>7</td>
</tr>
<tr>
<td>1.2.4</td>
<td>ANFIS controller</td>
<td>7</td>
</tr>
<tr>
<td>1.3</td>
<td>PROBLEM STATEMENT</td>
<td>10</td>
</tr>
<tr>
<td>1.4</td>
<td>OBJECTIVES AND CONTRIBUTION OF THE THESIS</td>
<td>10</td>
</tr>
<tr>
<td>1.4.1</td>
<td>Objectives of the Thesis</td>
<td>10</td>
</tr>
<tr>
<td>1.4.2</td>
<td>Contribution of the Thesis</td>
<td>10</td>
</tr>
<tr>
<td>1.5</td>
<td>THESIS ORGANIZATION</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>FUZZY PD AND FUZZY PID CONTROLLERS FOR THE SPEED CONTROL OF BRUSHLESS DC MOTOR</td>
<td>14</td>
</tr>
<tr>
<td>2.1</td>
<td>INTRODUCTION</td>
<td>14</td>
</tr>
<tr>
<td>2.2</td>
<td>SPEED CONTROL SCHEME FOR BRUSHLESS DC MOTOR</td>
<td>14</td>
</tr>
</tbody>
</table>
2.3 DESIGN OF FUZZY PD AND FUZZY PID TYPE SPEED Controller for the Brushless DC Motor 16
2.3.1 Conventional PD and PID controller 16
2.3.2 Design of fuzzy PD controller 17
2.3.3 Design of fuzzy PID controller 21

2.4 FORMULATION OF THE OBJECTIVE FUNCTIONS FOR TUNING OF FUZZY PD AND FUZZY PID CONTROLLER 22

2.5 REVIEW OF NATURE-INSPIRED OPTIMIZATION ALGORITHMS FOR TUNING OF FUZZY PD AND FUZZY PID CONTROLLER 25
2.5.1 Particle swarm optimization 25
2.5.2 Cuckoo search algorithm 27
2.5.3 Bat algorithm 27

2.6 OPTIMIZATION RESULTS AND DISCUSSIONS 30
2.6.1 Initial parameter settings 30
2.6.2 Optimization results for fuzzy PD controller and fuzzy PID controller 32

2.7 SIMULATIONS RESULTS AND DISCUSSIONS 43
2.7.1 Operating condition 1 43
2.7.2 Operating condition 2 45
2.7.3 Operating condition 3 47

2.8 EXPERIMENTAL SET UP AND RESULTS DISCUSSION 49

2.9 SUMMARY 52

3 FUZZY PID SUPERVISED ONLINE RADIAL BASIS FUNCTION NEURAL NETWORK BASED SPEED Controller for Brushless DC Motor 53
3.1 INTRODUCTION 53
3.2 DESIGN APPROACH OF FUZZY PID SUPERVISED ONLINE RADIAL BASIS FUNCTION NEURAL NETWORK CONTROLLER 53

3.3 DEVELOPMENT OF FUZZY PID SUPERVISED ALGORITHM 54

3.4 DEVELOPMENT OF ONLINE SUPERVISED RADIAL BASIS FUNCTION NEURAL NETWORK 58

3.5 SIMULATION RESULTS AND DISCUSSION 61
  3.5.1 Speed response for varying load condition 62
  3.5.2 Speed response for varying set speed condition 64

3.6 SUMMARY 65

4 FUZZY TUNED PID SUPERVISED OFFLINE ADAPTIVE NEURO FUZZY INFERENC SYSTEM BASED CONTROLLER FOR BRUSHLESS DC MOTOR 66

4.1 INTRODUCTION 66

4.2 ADAPTIVE NEURO-FUZZY INFERENC SYSTEM (ANFIS) BASED CONTROLLER 66

4.3 FUZZY TUNED PID SUPERVISED OFFLINE ANFIS CONTROL SCHEME FOR SPEED CONTROL OF BRUSHLESS DC MOTOR 68

4.4 DEVELOPMENT OF SIMULINK MODEL AND TRAINING OF FUZZY TUNED PID SUPERVISED OFFLINE ANFIS CONTROLLER USING MATLAB 73
  4.4.1 Simulation results and discussion 80
    4.4.1.1 Response of the motor for constant load condition 82
    4.4.1.2 Response of the drive under varying load conditions 83
    4.4.1.3 Response of the drive for step change in reference speed 86
4.5 SUMMARY 87

5 FUZZY PID SUPERVISED ONLINE ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM BASED CONTROLLER FOR BRUSHLESS DC MOTOR 88

5.1 INTRODUCTION 88

5.2 DESIGN OF FUZZY PID SUPERVISED ONLINE ANFIS CONTROLLER 89

5.3 SIMULATION RESULTS AND DISCUSSIONS 98

5.3.1 Result for constant load condition 98

5.3.2 Result for varying load condition 101

5.3.3 Result for varying set speed condition 104

5.3.4 Comments on results and discussion 106

5.4 SUMMARY 107

6 BAT ALGORITHM OPTIMIZED ADAPTIVE NEURO-FUZZY INFERENCE SYSTEM BASED SPEED CONTROLLER FOR BRUSHLESS DC MOTOR 108

6.1 INTRODUCTION 108

6.2 BAT ALGORITHM OPTIMIZED ONLINE ANFIS BASED SPEED CONTROLLER FOR BRUSHLESS DC MOTOR 108

6.2.1 PID control training data 110

6.2.2 Online Adaptive Neuro-Fuzzy Inference System 111

6.2.3 Learning parameter update law for the online ANFIS controller 115

6.3 TUNING OF LEARNING PARAMETER OF THE ONLINE ANFIS CONTROLLER USING BAT ALGORITHM 117

6.4 TUNING OF GAIN PARAMETERS OF THE PID, FUZZY PID AND ADAPTIVE FUZZY LOGIC CONTROLLER USING GA, PSO AND BAT ALGORITHM 128

6.5 SIMULATION RESULTS AND DISCUSSION 132
6.5.1 Simulink model of bat algorithm optimized online ANFIS based speed controller for Brushless DC Motor 132
6.5.2 Simulation result for constant load condition 134
6.5.3 Simulation result for varying load condition 136
6.5.4 Simulation result for varying set speed condition 139
6.6 EXPERIMENTAL SET UP AND VERIFICATION 141
6.6.1 Experimental setup 141
6.6.2 Experimental verification of controller performance 144
6.7 SUMMARY 146

7 CONCLUSION AND SCOPE FOR FUTURE WORK 147
7.1 CONCLUSION 147
7.2 SCOPE FOR FUTURE WORK 149

REFERENCES 150

LIST OF PUBLICATIONS 156